Proposal Cover Sheet

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Title: The Interaction Between the Troposphere and the Stratosphere: The Impact of Climate Change

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Program Element

EOS Interdisciplinary Science Program (EOS/IDS)

The Interaction Between the Troposphere and the Stratosphere: The Impact of Climate Change

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Statement of relevance: This proposal is relevant to the EOS IDS program because it uses a variety of different data sets (chemical, meteorological, radiative, microphysical) from multiple platforms, because the modeling studies include cross disciplinary activities, and because the results of the studies will impact multiple disciplines.

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Abstract

We propose to study the process of stratosphere-troposphere exchange using the EOS and pre-EOS satellite and aircraft/balloon data sets as well as models. The science questions we intend to address are: 1) can we quantify the process of stratosphere-troposphere exchange (STE) to determine if models correctly characterize the transfer of trace gases between the stratosphere and troposphere, and 2) how will the STE process be modified by the increase in greenhouse gases. The proposal consists of both modeling and data analysis elements. The data analysis elements are oriented toward characterizing STE by analyzing aerosol and trace gas data from both the stratosphere and the troposphere. As part of our data analysis effort we intend to produce a tropospheric ozone data product. The modeling elements are oriented toward using the new NASA/NCAR GCM combined with on-line chemical/ aerosol/ radiation models developed at GSFC and elsewhere to determine if our current understanding of the STE process is quantitatively correct. At the end of the three-year proposal period we expect to have completed several greenhouse gas growth scenario runs. These analyses will enable us to estimate how the STE process may be modified in a future atmosphere, and how the stratosphere and troposphere will be changed chemically as a result.

1.0 Introduction

1.1 History and Strategic Approach

We propose to continue the previous IDS (PIDS) investigation originally titled "A Proposal to Investigate the Chemical and Dynamical Changes in the Stratosphere Up to and During the EOS Observing Period." The original proposal was funded in 1989 and reviewed in 1994. Because the EOS platforms did not launch during the previous proposal period, the PIDS took advantage of aircraft (AASE II, STRAT, SPADE, POLARIS, TOTE/VOTE, SONEX, ASHOE/MAESA, PEM-Topics) and balloon (OMS) data as well as Upper Atmospheric Research Satellite (UARS), Stratospheric Aerosol and Gas Experiment (SAGE) II and Total Ozone Mapping Spectrometer (TOMS) observations to develop both data analysis and modeling tools that are described in Appendix A. The goals of this IDS proposal are focussed on a new set of science questions that confront the community. In this proposal we intend to use the tools and models developed by our PIDS and other EOS investigations to study stratosphere-troposphere exchange (STE). We propose to increase our quantitative knowledge of the UT/LS and to identify better the mechanisms responsible for STE. Further, through diagnostic and predictive studies, we plan to determine the sensitivity of these mechanisms to changing climate parameters.

Within the PIDS and related proposals we have developed a set of unique quantitative tools to study transport dynamics and reactive chemistry. Our simultaneous treatment of aircraft, balloon, and satellite observations bring together local and global processes. Our use of assimilation models and fast chemical transport and trajectory models has helped us interpret observations as well as make significant improvements in the models. The past research points to promising new techniques that will allow even more quantitative interpretation of past and future observations and that are well-suited to addressing STE issues. This proposal brings together these tools with our proven capability of quantitative analysis and a new generation of predictive models to study the role of stratosphere-troposphere exchange in the chemistry-climate system.

This IDS proposal is being coordinated with several other ACMAP and IDS investigations whose research is highly relevant to this investigation. The approach of coordinating this IDS effort with other efforts is being taken to (1) provide more scientific depth for certain areas (2) to allow younger investigators, partially funded under the PIDS, to develop their own research agendas (3) to augment the development of the "Combined Stratosphere-Troposphere Model" discussed below. The

collaborative proposals are listed in Appendix B. Each of the collaborative proposals and this proposal stand alone, but we expect that the scientific progress of all of the proposals in this confederation will be enhanced by the collaboration.

1.2 Background

As our ability to understand the processes affecting stratospheric ozone has improved, increasing importance is being given to the lowermost stratosphere and the uppermost troposphere (LS/UT). Historically, the stratosphere and troposphere have been viewed as more or less distinct domains, with the transport of trace constituents between the two domains being the residual effect of complex dynamical processes within each domain. To more completely quantify atmospheric chemical processes and their impact on the climate system, we must increase our understanding of and ability to simulate the radiative, dynamical, and chemical processes in the transition region between the troposphere and the stratosphere, and the exchange of gases between the two regions.

A good review of stratosphere-troposphere exchange was given by Holton et al. (1995) (H95). H95 argued that the conceptual model of stratospheric-troposphere exchange (STE) based on the notion of a wave-driven pump (McIntyre, 1992) inducing upward motion at the tropical tropopause with downward motion at middle and high latitudes provides an effective paradigm for STE. In fact, this global dynamic framework, most clearly appropriate for the stratospheric overworld, is often more effective than explicit consideration of the rich variety of dynamical events that occur in the vicinity of the tropopause [e.g. WMO, 1986, Danielsen et al., 1970; Shapiro, 1980; Lamarque and Hess, 1994; Langford et al., 1996; Beekmann et al., 1997, Bamber et al., 1984; Vaughan and Price, 1989; Price, 1990; Price and Vaughan, 1993; Ancellet et al., 1994]. Improved observations and modeling capabilities since the H95 review have led to important refinements of the schematic view of STE.

The tropopause is a complex internal boundary within the atmosphere related to both radiative and dynamical mechanisms (Thuburn and Craig, 1997). Figure 1 shows the different regimes of the zonally averaged atmosphere. Of particular note is the tropical sub-stratosphere which is the region below the thermal tropical tropopause and above the top of the bulk of the deep tropical convection. Folkins et al. (1999, their Figure 1) provides examples where the ozone starts to increase to stratospheric values on the order of 3.5 km below the nominal tropopause. These observations can also be seen in the STRAT dive data (our Figure 2). The maintenance of temperature, ozone, water vapor and the profiles of other tracers in this upper tropospheric region are difficult to explain with conventional concepts of convective overshooting and the stratospheric “fountain” (a preferred longitude for entry of air into the stratosphere, Newell and Gould-Stuart, 1983).

Similarly, modeling studies at mid-latitudes show that the middleworld stratosphere (the region of the stratosphere between the tropopause and 380 K) exchanges mass with the troposphere on much shorter time scales than the stratosphere above 380K [e.g., Schoeberl et al., 1998, Gettelman, et al., 1999]. Transport diagnostics derived from meteorological analyses, including 3-D tracer calculations, suggests that mixing associated with Rossby waves keeps the middle latitude upper troposphere and lower stratosphere more stirred than historically believed. This means that while consideration of how much mass flows across the 380 K surface might indicate how much stratospheric air is available for transport into the troposphere, the amount of mass flux across the tropopause itself is probably significantly larger because of local mixing. In total, research in the past five years and more stringent demands on assessment models, suggest that our understanding of STE is incomplete and needs to be refined.

The importance of the UT/LS in chemistry and climate problems is well stated in a number of international assessment documents (e.g. Houghton et al., 1995, Kawa et al., 1999, Penner et al., 1999). There are fundamental climate-change questions related to moistening or drying of the upper troposphere as convective activity changes. Because the concentrations of many trace gases vary greatly across the tropopause, changes in the UT/LS impact not only the radiative attributes of the atmosphere, but also the chemical environment. Within the context of chemical problems one of the largest uncertainties is how much ozone and odd nitrogen is supplied to the troposphere from the stratosphere.

1.3 Some specific issues associated with STE and climate change

As previously mentioned a good conceptual model of the stratospheric circulation is that of a poleward pump driven by breaking planetary waves in winter. As this pump moves material poleward, by mass continuity, air must rise in the tropics and sink at polar latitudes. This concept has been clearly documented in satellite and in situ trace gas observations (Mote et al., 1996, Russell et al., 1993, Schoeberl et al, 1995, and others). By definition, the exchange of air between the overworld stratosphere and lower atmosphere is controlled by the rate at which the air crosses the 380K surface. Diabatic descent occurs throughout the seasons at the boundary between the middleworld stratosphere and the overworld stratosphere (Appenzeller et al., 1996, Schoeberl et al., 1998), and ascent occurs in the tropics. Because of the diabatic descent, it is very unlikely for gases which have entered the middleworld stratosphere to move directly into the overworld stratosphere. Thus air can only enter the overworld through the tropical tropopause.

Trace gases enter the stratospheric middleworld from both the troposphere (e.g. Rood et al., 1992) and from the stratospheric overworld, the latter being rich in ozone and other stratospheric trace gases. Since the lifetime of air within the middleworld is short, about 2-3 months (Schoeberl et al.,1998, 1999), there is a strong link between the amount of ozone in the troposphere (exchanged via the middleworld) and the large scale circulation of the stratosphere which controls the flux of ozone across the 380K surface. Unfortunately estimates of the amount of mass exchanged across the extra-tropical 380K surface are uncertain to 30% or higher [Appenzeller et al., 1996, Yang and Tung,1996]. This uncertainty estimate comes mainly from the imbalance in the globally integrated heating rates [Shine, 1989, Olaguer et al., 1992].

Despite the uncertainty, the approach of estimating the stratospheric component of tropospheric ozone by examining the large scale circulation appears to be far more fruitful than estimating transfer from the stratosphere to the troposphere via tropopause folds or cut-off lows(see WMO, 1986, Chapter 5 for a review). While fold and cut-off low dynamics have been studied extensively, it is still not clear how much stratospheric air is irreversibly transferred into the troposphere on a global scale by stratospheric intrusion events. It also is not clear whether spectacular folds are responsible for most of the flux of mass from the stratosphere or whether the more frequent smaller intrusions transfer the bulk of the mass into the troposphere (H95).

North-South transfer of upper tropospheric trace gases into the middleworld stratosphere is often seen in the spring. Rood et al. [1992], for example, discuss the case of a spectacular northward intrusion of tropospheric tropical air entering the middleworld stratosphere. The scale of this event was so large that it was observed by the Microwave Limb Sounder (MLS) on board UARS. Recently Postel and Hitchman [1999] have identified additional preferred regions of mass transfer between the tropical upper troposphere and the middleworld stratosphere. These regions occur near summer monsoons where the isentropes extend from the middleworld stratosphere into the tropical troposphere and the flow is north-south. Monsoon transfer may dominate the exchange between the middleworld stratosphere and the troposphere in the summer hemisphere.

The stratospheric middleworld is a highly variable region. During winter, the mid-latitude 380K surface rises and the tropopause descends. The volume of the stratospheric middleworld increases. Air within this region becomes more stratospheric in character when the mass transfer from the overworld across the 380 K surface increases due to diabatic descent. By the end of winter, trace gas measurements show that 60-80% stratospheric middleworld air may have come from the overworld [Ray et al., 1999]. The depth of the stratospheric middleworld also varies under the influence of the tropospheric weather systems. Figure 3a shows an estimate of the mass within the stratospheric middleworld. Figure 3b shows that synoptic influence extends into the overworld; that is, the downward flux into the middleworld across the 380K surface is modulated by the synoptic systems extending upward from the troposphere. Figure 4 shows mass budget computations of the middleworld stratosphere and fluxes into the stratosphere and troposphere for three years using the technique of Appenzeller et al. [1996]. The year to year variations of mass of the middleworld stratosphere (1995-1997) are all remarkably similar: In late winter and spring, the stratospheric middleworld shrinks as the tropopause rises. This process reverses with the onset of winter [Appenzeller et al., 1996]. These variations are more dramatic in the Northern Hemisphere compared to the Southern Hemisphere. As the middleworld during spring shrinks (Figure 4) there is an increasing flux of stratospheric middleworld air into the troposphere and the diabatic descent from the stratosphere slows. This flux drops almost by a factor of two during summer and early fall compared to late winter. Trace gas measurement show only 20% of the summer stratospheric middleworld air characteristic of the overworld stratosphere [Ray op cit.].

Tropospheric air enters the overworld stratosphere across the tropical tropopause boundary. Until recently it was thought that all the air entered the stratosphere in the west Pacific “fountain” region as proposed by Newell and Gould-Stuart [1981]. Most recently, work partially funded under the PIDS has shown that water vapor meteorological data do not indicate a preferential upwelling zone [Dessler, 1998] a result consistent with recent numerical model simulations using the GEOS-DAS [Gettelman et al., 1999]. Although the stratospheric wave-breaking pump controls the ascent rate in the tropical lower stratosphere (the Brewer-Dobson circulation), it does not entirely control the amount of air crossing the tropical tropopause because the influence of the pump is reduced both with altitude and latitude [Plumb, 1999]**.** The 380K surface is the transition layer below which the Hadley circulation is dominant, and above which the Brewer-Dobson circulation is dominant. Indeed, the magnitude of the water vapor mixing ratio at the tropopause appears to be set by tropical convective processes that vary with the Hadley cell strength. A recent study under the PIDS [Sherwood, 1999] found that stratospheric entry does not appear to take place in regions of deepest convection, contrary to common wisdom. Sherwood also found evidence for a weak descending circulation in the tropical sub-stratosphere in the west Pacific. He suggested that overshooting turrets within deep-convective systems were cooling the layer around the tropopause and causing a secondary (descending) circulation to develop. Such a secondary circulation would be consistent with the tracer observations of Folkins et al. [1999].

Most of the air entering the tropical stratosphere moves poleward and back into the stratospheric middleworld, thus the upward flux of air into the tropical stratosphere reflects the seasonal variations seen at middle latitudes (Fig. 4). However, it is also evident from chemical measurements of the tropical lower stratosphere that tropical air is mixed with older mid-latitude air (Avallone and Prather, 1996, Minschwaner et al., 1996, Volk et al., 1996). Thus air within the mid-latitude stratosphere circulates back into the tropics, and clearly the tropical stratosphere is not completely isolated from mid-latitudes as originally suggested by Plumb [1996]. Even though the amount of tropical “leakiness” appears to vary with altitude [Schoeberl et al., 1997], the degree of tropical isolation and tropical cross-tropopause transport obviously affects the “age” of stratospheric air.

As greenhouse gases have increased, the lower stratosphere has cooled [Oort and Liu, , 1993; Spencer and Christy, 1993; Pawson et al., 1998]. This cooling may reduce the downward mass flux across the 380K surface by altering stratospheric "pump". A slowdown in the Brewer-Dobson circulation would increase the lifetime of gases within the stratosphere and slow the return of ozone destroying

chemicals to the troposphere. Indeed, Shindell et al. [1998], using the low horizontal resolution, GISS climate model, found that the stratospheric wave driven circulation slowed under an increasing greenhouse gas scenario. The decrease in planetary wave-driving created a colder polar vortex which increased winter polar ozone loss. However, Shindell et al. assumed that stratospheric water vapor would not be changed during the simulation, which is unlikely. Furthermore, the GISS model does a relatively poor job of simulating the distribution of long lived trace gases [Douglass et al., 1999; D. Waugh, private communication, 1999]. Nonetheless, the possibility raised by Shindell et al. [1998] that significant shifts in stratospheric dynamical transport could take place under global warming scenarios requires further investigation using improved models.

The rate at which air crosses the tropical tropopause is determined by the diabatic heating at the tropical tropopause. The cold tropical tropopause is a region of very weak net diabatic heating. General circulation models predict that as greenhouse gases increase, the tropical tropopause will warm as increased latent heat release warms the tropopause [Thuburn and Craig, 1997]. The recent discovery of sub-visible cirrus (SVC) over extensive regions of the tropics during NASA's TOTE/VOTE and CEPEX missions has led to a more complex picture of the tropical tropopause radiation budget. SVC warms the tropical tropopause by intercepting IR radiation from the warmer surface. If the amount of SVC increases as a result of global warming, the tropopause temperature will warm further allowing more water vapor into the stratosphere [Rosenfield et al., 1998]. In fact, recent analysis of multi-decadal balloon data shows an increase in stratospheric water vapor of 0.05 ppm/year [Rosenlof, Personal Communication, 1999; see also Oltmans and Hofmann, 1995]. The increase in stratospheric water vapor will increase the minimum temperature for polar stratospheric cloud (PSC) formation thereby making PSC formation more likely. An increase in PSC's would exacerbate polar ozone loss and slow the recovery of stratospheric ozone.

To summarize, the Shindell et al. [1998] study suggests a slowing of the future stratospheric circulation with a cooling of the future polar vortex, while observations of increasing water vapor in the stratosphere suggest a warmer tropopause which implies smaller tropical tropopause diabatic heating and reduced upwelling. The implications are (1) slower flushing of the stratosphere gases and thus a slower decrease in stratospheric chlorine (2) more frequent PSC's and more significant Arctic polar ozone loss.

As a result of STE, the stratosphere is a significant source of tropospheric ozone. Estimates of the stratospheric contribution to tropospheric ozone vary from 35%-10% depending on the model [Hauglustine et al., 1998]. Tropospheric ozone, aside from being a toxic pollutant, is a significant greenhouse gas [Lacis et al., 1990]. In addition, there is good evidence to believe that tropospheric ozone has increased in the northern mid-latitudes since pre-industrial times [Staehelin et al., 1994, Marenco et al., 1994]. Calculations of the radiative impact of the ozone increase vary from 0.2 to 0.6 Wm^{-2} [Houghton et al., 1995]. This wide range can be attributed to the short lifetime of tropospheric ozone (on the order of a few weeks) which leads to a highly variable distribution of tropospheric ozone. Adding to the uncertainty in the tropospheric ozone variability is the stratospheric ozone contribution due to STE because STE's are strongly correlated with meteorological events and vary with short term climate change (WMO, 1986, Langford, 1999). It is upper tropospheric ozone which is most affected by STE and which also has the strongest climate forcing [Lacis et al, 1990]. Thus, even though the contribution of stratospheric ozone to the total tropospheric ozone burden is expected to decrease as pollution-driven surface ozone sources increase, the stratospheric impact on the tropospheric ozone-forced climate change will probably remain significant.

Knowing the net flux of air into (and out of) the troposphere from (to) the stratosphere is a key issue for both stratospheric and tropospheric chemistry. This issue impacts our understanding of the chemical processes of both regions – both the budget of tropospheric ozone and the budget of stratospheric trace gases that control stratospheric ozone. The discussion above is intended to show how the stratospheric and tropospheric processes are linked chemically and dynamically, and that

neither a single data set nor a single model can address all the complex processes and feedbacks. Thus, this IDS investigation outlines an approach that takes advantage of (1) extensive research and tool development from our PIDS (2) coordination with other IDS investigations (3) models developed by the Data Assimilation Office (DAO) and ACMAP-funded investigations.

1.4 Science Questions

The main science questions we intend to focus on are:

1) What are the dynamical processes that control the exchange of trace gases between the troposphere and the stratosphere and what are their magnitudes?

2) Is our understanding of the tropospheric and stratospheric chemical processes that are impacted by STE consistent with the observational data?

3) How will increasing greenhouse gases alter the exchange rate between the troposphere and the stratosphere, and how will the change in exchange rate alter the chemistry of both the stratosphere and the troposphere?

2.0 Scope of Proposed Activity

2.1 Science Strategy and Tactics

The goal of this IDS proposal is to quantify the process of stratosphere-troposphere interaction and exchange of trace gases as outlined in the science questions. We also propose to assess how climate change will affect the stratosphere-troposphere exchange process. This proposal plans to

1) Provide an improved estimate of the amount of trace gases (especially ozone and water vapor) exchanged between the stratosphere and troposphere,
2) Gain a better understanding of the processes which control the exchange between the stratosphere and troposphere,
3) Determine if the stratosphere-troposphere exchange process can be correctly represented in the new generation of models developed for data assimilation and climate research, and
4) Determine how the stratosphere-troposphere exchange process will be altered by the increase in greenhouse gases.

Our tactical approach to achieving these goals is to:

(1) Continue our analysis of existing data sets using the tools developed under the PIDS, and to apply these techniques to the new EOS data sets which will become available during the proposal period.
(2) Develop an improved tropospheric ozone product using the dynamical tools developed under the PIDS. We believe that this product is important because it will be a good diagnostic of STE, and because tropospheric ozone is of increasing importance to climate change and tropospheric chemistry,
(3) Determine if STE can be correctly modeled in the new generation of models. We intend to apply our diagnostic tools to the new NASA/NCAR GCM. Aside from the dynamics analysis (see Newman ACMAP proposal, Appendix B) we intend to focus on tracer studies. To do this we also intend to develop a new chemical-dynamical-radiative model of stratosphere-troposphere interaction. This model, which we will refer to as the "Combined Model," will be based upon the NASA/NCAR GCM which uses the CCM 3 physics package (Appendix C.1) and will incorporate chemical and microphysical packages developed under this proposal and collaborative proposals.

Part of the stratospheric chemical package (Appendix C.2) has already been coupled with this model. Within the first year of the proposal, both the microphysical and chemical packages from the GOCART tropospheric chemistry packages (Appendix C.3, C5.1) will also be coupled. At a later date a version of the model with the Toon microphysical package (Appendix C5.2) will be tested.

(4) Finally, using the Combined Model we intend to determine the impact of increasing greenhouse gases on the stratospheric circulation, STE and upper tropospheric chemical processes.

2.2 The Combined Model

To answer the science question of the impact climate change will have on STE we need to have physically realistic dynamical-chemical-radiative models of both the stratosphere and the troposphere. The basic dynamical model will be the joint NASA/NCAR dynamical model described by Lin and Rood [1999] (Appendix C.1). The NASA/NCAR GCM will be used as the core model for the next generation DAO assimilation model currently well along in development. The design of this model makes easy to attach physics and chemistry modules, the code is built to simultaneously transport a variable number of tracers, and has better mass conservation properties than previous generation GCM's. The collaboration between DAO and NCAR means that state-of-the-art tropospheric physics (CCM 3 & 4 packages) will be included and updated in the model.

Chemical models of the stratosphere and troposphere have had different development paths because the photochemical processes that dominate these regions are different. Stratospheric models emphasize the catalytic ozone destruction cycles including chlorine and bromine chemistry, and the heterogeneous chemistry of the chlorine and nitrogen reservoir gases on aerosols. Tropospheric chemistry emphasizes hydrocarbon, HO_x and NO_x processes neglecting, generally, heterogeneous processes. Rather than develop a unified model of atmospheric chemistry, we intend to attach the state-of the art chemical modules developed for the stratosphere and troposphere to the NASA/NCAR GCM.

A key to exploring the impact of STE on both the stratospheric and the tropospheric chemical process is correctly estimating the ozone flux between the two regions. Rind et al. [1999] has shown that to correctly simulate the mass flux good resolution and gravity wave drag are required in the stratosphere, and there is considerable anecdotal evidence that tropospheric chemistry models which have poor stratospheric resolution generate physically unrealistic stratospheric to tropospheric ozone fluxes.

Our approach will be to systematically include chemical modules as we diagnose the model response expanding the evaluation approach outlined in Douglass et al. [1999] for the stratosphere. One advantage we will have is that we will be able to continue to influence the development of the NASA/NCAR GCM in this phase. This approach has not been used historically - GCM's are usually not developed with the transport systems and chemical modules functioning in-line. Rather the chemical transport codes are usually used as off-line diagnostic tools.

Initially we will use the chemistry modules developed by Douglass under ACMAP (Appendix C.2) for the stratosphere. Figure 5 shows preliminary results from the NASA/NCAR GCM running with parameterized stratospheric chemistry (no heterogeneous chemistry). Comparisons with TOMS show little tropical bias and mid-latitude bias; however, the polar vortex simulations need to be improved.

For the tropospheric chemistry, we will use the modules from the GOCART model (Goddard Ozone Chemistry Aerosol Radiation and Transport model). This model used the Goddard Chemical Transport Model (CTM) in the tropospheric aerosol simulations [Chin et al., 1999]. Currently the GOCART chemical package uses prescribed oxidant concentrations (OH, H_2O_2, O_3, NO_3) in modeling tropospheric sulfur. We will implement the complete chemistry and surface emission modules for tropospheric ozone and related species into the GOCART model (Appendix C.3) for

testing and then into the NASA/NCAR GCM after determining how extensive a chemical package is required.

To answer the question of radiative feedbacks due to aerosols, we will use the GOCART tropospheric aerosol modules (Appendix C.5.1). In the past few years, these modules in the CTM have been used to simulate sulfate, dust, sea salt, and carbonaceous aerosols [Chin et al., 1999; Ginoux et al., 1999]. The model calculated aerosol concentrations compares well with ground based, in-situ field, sun photometer, and satellite observations. However, currently the GOCART aerosol simulation does not include complete aerosol microphysics. To better estimate the aerosol optical properties, we intend to develop a microphysics capability in the model (Appendix C.5.1).

The proposed Combined Model should be distinguished from the AEAP's Global Modeling Initiative (GMI) model, although many of the CoI's have been part of the GMI effort, and we also intend to draw on the experience we have had with GMI. The Combined Model will be a free running GCM; it is a research model, not an assessment model such as the GMI model. I this proposal, the Combined Model, will be used primarily to investigate STE, and we expect that much of what we learn from the Combined model will be applicable to the GMI effort and vice versa.

2.3 Quantifying STE: Comparing Observations and Simulations

There are a large number of data sets that are already available to examine the STE processes. The most useful of these are the UARS and SAGE II data sets that monitored the Mt. Pinatubo eruption. The decay of the sulfate aerosol cloud generated by Mt. Pinatubo provided a unique opportunity to test the effect of STE in our global models. Although a number of investigations (listed in the next section) have simulated the decay, the finally processed UARS data set provides an improved and enhanced picture of the dynamics of the event.

2.3.1-1 Aerosol Studies: Data Analysis

An important step in quantifying future changes in STE is determining if current GCM simulations of the locations and magnitude of STE are correct. Unfortunately, until the launch of EOS CHEM, there will be no instruments that have sufficient global coverage or sensitivity to observe the transfer of ozone or overworld stratospheric trace gases into the middleworld stratosphere or across the tropopause. (MOPITT and SCIAMACHY are possible exceptions as discussed below). An alternative approach is to examine the observed STE associated with the transfer of Mt. Pinatubo volcanic aerosol from the stratosphere to the troposphere. The 20 megaton Mount Pinatubo (15^{o}N, 120^{o}E) SO_2 injection in June of 1991 [Bluth et al., 1992] increased the stratospheric sulfate aerosol loading by over 2 orders of magnitude above background [McCormick and Veiga, 1992]. The resulting sulfate aerosol cloud was mostly situated between 20 and 25 km in the tropics. Aerosol moved out of the tropics into the southern hemisphere via an interaction between mid-latitude planetary waves and QBO easterlies at 30 hPa. Transport into the Northern Hemisphere was associated with synoptic scale systems connected to the Asian monsoon [Trepte et al., 1993] consistent with the later analysis of Postel and Hitchman [1999].

A number of 2D model studies (including our own) have focused on separating the influence on ozone concentrations of the chemical, dynamical, and radiative changes induced by Pinatubo [Brasseur and Granier, 1992, Pitari and Rizi, 1993, Kinnison et al., 1994, Bekki and Pyle, 1994, Tie et al., 1994, Rosenfield et al., 1997]. The 3D model studies have focused primarily on modeling the early evolution of the volcanic cloud in the stratosphere either as a passive tracer [Boville et al., 1991, Mote et al. 1994, Rodgers et al., 1998] or considering the radiative influence of the aerosols [Young et al., 1994, Timmreck et al., 1999, Rodgers, et al. 1999].

In order to better understand STE, we propose to further exploit the Mount Pinatubo eruption observations. Trepte et al. [1993] used SAGE II aerosol data to study the tropical stratospheric

reservoir; however, only a few studies have examined STE in the context of the Mount Pinatubo eruption. Clearly, the rate of flushing of aerosol from the stratosphere depends sensitively on STE. For example, Timmreck et al. [1999] had to reduce vertical advection across the 380 K surface by 75% to reproduce the observed rate of stratospheric cleansing in the ECHAM4 GCM.

Radiative feedbacks are clearly important in simulating the Pinatubo cloud since sulfate aerosols are efficient absorbers of longwave radiation. Estimates of the Pinatubo driven heating rate changes in the lower stratosphere range up to about 0.5 K/day, which would produce substantial increases in tropical vertical velocities. (e.g. Eluszkiewicz et al., 1997) as well as an uplift in the ozone layer which was observed [Schoeberl et al, 1992]. The increase in tropical vertical upwelling due to the aerosol radiative heating implies by continuity either that transport across the stratospheric tropical barriers or across the tropical tropopause must increase. Thus the Pinatubo eruption might have decreased the mean age of the stratosphere by increasing the amount of young air entering the stratosphere, or increased it by increasing the mixing of older air back into the tropics. In our current investigation of the effects of Pinatubo using the GSFC interactive 2D model we also find substantial increases in the amount of H_2O entering the stratosphere due to a warmer tropical tropopause, although it is unclear if a Pinatubo signal in water vapor was observed.

We believe the combination of aerosol and trace gas information from the recently released final reprocessed UARS (ISAMS, CLAES and HALOE) and the reprocessed SAGE II data will provide quantitative information on the STE process associated with Pinatubo.

A key element of this effort will be improved meteorological fields during the eruption period. UKMO assimilation data begins with the launch of UARS (mid -September, 1991, 3 months after the eruption and reprocessed NMC data extends only to 10 hPa. As a result we are teaming with one of the collaborative proposals (see Appendix B, Pawson) which proposes to re-assimilate the 1991-1995 period using the newest version of the assimilation system. This would produce an improved assimilated data set to drive CTM studies which we will then compare with CM simulations.

2.3.1.2 Aerosol studies: Using the Combined Model

We will simulate the Mount Pinatubo eruption using the chemical trajectory model (Appendix A.2.a) with the improved assimilated meteorology , and interactively using the Combined Model. The Combined Model will include all the components necessary to create a sophisticated interactive simulation of the Pinatubo volcanic cloud and examine its effects. For instance, the Combined Model physics package already includes the tropospheric hydrological process and water vapor transport so it can be used to study the effect of Pinatubo on H_2O transport across the tropopause, which our 2D model simulations suggest may have changed due to tropopause warming..

We also will use our trajectory model to diagnose the transport of the Pinatubo aerosol. Figure 6 shows a prototype trajectory simulation of a tropically released aerosol (January 1, 1992) - similar to the Pinatubo case using the new fast trajectory model. As with the Pinatubo aerosol, material moves downward into the stratospheric middleworld and then into the troposphere but with a seasonal preference. First, the aerosol moves toward the northern middleworld then toward the southern (consistent with the observed initial transport of Pinatubo aerosol into the

Southern Hemisphere after the June eruption). Note the remaining material in the tropical reservoir even a year after integration.

To track the aerosols once they reach the troposphere aerosols we will use the GOCART sulfur chemistry and aerosol packages (Appendix C.5.1). The more computationally expensive Toon microphysical package (Appendix C.5.2) will be used to check the simulations. Although they cannot be predicted, we expect that smaller scale eruptions (ash and SO_2 gas injection) into the middleworld stratosphere will occur during the proposal time frame and will be available for study. In particular, we will investigate the following questions: 1. Does the modeled exchange of mass between the stratosphere and troposphere result in correct stratospheric cleansing rates? 2. How is this mass exchange changed by the presence of the volcanic aerosols? 3. How was the transport of ozone from the stratosphere to the troposphere affected by the eruption? 4. How was stratospheric water affected by the eruption?

At this point it is worth noting the need for a more complex treatment of aerosols - not just sulfate aerosols - in the upper troposphere has been has been clearly argued by Tabazadeh et al. [1998]. The SUCCESS (Toon and Miake-Lye, 1998) and WAM (Murphy et al., 1998) missions both observed an unexpected variety of aerosol types in the upper troposphere. Tabazadeh et al. argue that mineral dust and biomass burning aerosols observed in the upper troposphere provide an important sink for gas phase nitric acid in the upper troposphere. Nitric acid amounts in current tropospheric chemistry models are often twice to four times larger than have been observed (Thakur et al., 1999). Rapid conversion of nitric acid to nitrogen oxides on these aerosols could have a significant impact on upper tropospheric ozone which is partially controlled by nitrogen oxides. This is the motivation behind using the Toon microphysical model for some parts of the integration where the possibility of complex chemical and microphysical interactions in the upper troposphere might take place.

2.3.2-1 Tracer Studies: Data Analysis

Following the launch of TERRA, we also intend to use the CO data from MOPITT to investigate STE. The upper level CO data from MOPITT should show the mixing of low stratospheric CO amounts with the higher tropospheric CO values. With the launch of PM we intend to use the AIRS improved temperature fields to greatly improve our global estimates of the exchange of mass between the troposphere and stratosphere (as shown in Fig. 4) using our radiative transfer model (Appendix C.4). MODIS cloud data will also be useful in our computation of the heating and cooling rates at 380K and at the tropopause. Finally we intend to exploit the constituent data from ENVISAT (GOMOS, SCIAMACHY and MIPAS). These data sets will be compared with the chemical transport model computations of the same trace gases.

Although this proposal will focus on mid-latitude STE, the links to tropical STE cannot be ignored. One tropical issue we intend to investigate is the appearance of high amounts of ozone well below the tropopause (See Fig 2.). The Dessler IDS (Appendix B) is looking at trace gas transfer between the lower tropical stratosphere and the tropical sub-stratosphere. Alternatively, air could be moving horizontally from the upper middleworld stratosphere into the tropics and enriching the ozone distribution in the tropical sub-stratosphere. MOPITT observations may be able to test this hypothesis since upper middleworld CO is substantially lower than lower tropical stratospheric CO. Thus, one signature of the origin air within the tropical sub-stratosphere is high values of the ratio of ozone to CO.

2.3.2-2 Tracer Studies: Using the Combined Model

To prepare for the Pinatubo simulation, we also propose to carry out a series of idealized passive tracer experiments to test the sensitivity of the NASA/NCAR GCM to resolution. Starting from a normal initial state, the GCM model will be run for short period (e.g.30 days) with a suite of tracers

initialized to assess the transport from the stratospheric middleworld to the troposphere. Simple tracer distributions which will provide useful information are: (i) filling the region between the tropopause and the 380K isentrope; (ii) set equal to the initial potential vorticity; (iii) set equal to the initial potential temperature; (iv) values set to unity on the tropopause but zero elsewhere. More complete sets of tracers will be derived as the complexity of the problem becomes apparent. By varying both the horizontal and vertical resolution and making parallel trajectory model runs, it will become clear whether (a) convergence can be achieved in the rate of cross-tropopause transport and (b) what resolution represents an acceptable compromise between absolute accuracy and computational requirements. Additionally we intend to run global diagnostics of mass exchange (e.g. Appenzeller et al., 1996) and compare the model with observations (Fig. 4) Establishing the resolution of the model needed for properly represent STE is an important first step in this investigation.

2.3.3 Tropospheric ozone as a diagnostic of STE

As mentioned above, between 10%-30% of the tropospheric ozone amount has a stratospheric origin, and this percentage is probably much higher if we consider only the ozone found above 400 hPa in the ozonesonde climatology of Logan [1999]. The fact that tropospheric ozone lifetime is short (few weeks) means that STE events will be evident in the tropospheric ozone column as has been observed [Langford, 1999].

Tropospheric ozone amounts should provide a good diagnostic of STE, and will allow us to check our STE estimates using an important tracer. Unfortunately, there is very little available global tropospheric ozone data outside of the tropics. Thus we propose to develop an improved record of the tropospheric ozone distribution using currently available data sets. The purpose of developing this climatology is to allow us to compare our model estimates of the overall changes in tropospheric ozone in response to STE with observations. Tropospheric ozone can be estimated from TOMS data using the Fishman residual concept. This technique involves the subtraction of stratospheric ozone from TOMS total ozone using SAGE or HALOE ozone profiles (Fishman et al., 1990, 1991, 1996). The Fishman concept, however, is only accurate when the profile data and TOMS observations are co-located. Other approaches include TOMS cloud differentials (Ziemke et al.,1998), TOMS mountain-ocean differentials (Jiang and Yung,1996; Kim and Newchurch, 1996) and TOMS-ozonesondes differentials (Hudson and Thompson, 1998; Thompson and Hudson, 1999). The latter group of techniques works well only inside the tropics where the stratospheric ozone field is changing slowly.

2.3.3-1 Tropospheric Ozone Data Product

We propose to develop a tropospheric ozone product that extends to the mid-latitudes. The approach will be based upon the Fishman residual concept, but we will use our PV/PT stratospheric ozone climatology (see Appendix A.2.1 for discussion of the PV/PT method). We have developed this monthly climatology from SAGE II, HALOE, POAM and ozonesonde data (Figure 7) to improve first guess estimates for SBUV2 retrievals. Using the climatology, the local stratospheric ozone column can be estimated from meteorological maps of PV (see Schoeberl and Lait, 1992). The stratospheric ozone column can then be subtracted from TOMS data to generate a global tropospheric ozone residual. Since stratospheric meteorological variability is included, this method allows us to produce daily tropospheric ozone residuals outside the tropics. We also plan to use the more precise trajectory mapping method along with the SAGE II and HALOE profiles (Morris et al., 1995) to estimate the stratospheric ozone amount. These computationally expensive trajectory runs have already been performed as part of the HALOE/SAGE II comparison project (See Appendix A2.1), so the development of the tropospheric ozone product should be straightforward. A preliminary estimate of tropospheric ozone using the PV/PT technique is shown in Figure 7b. Of course, care must be taken to untangle the affect of local tropospheric pollution sources so our initial focus will be

on clean regions of the Southern Hemisphere troposphere where SHADOZ data are available (see Thompson proposal, Appendix B).

Toward the end of the proposal period, we plan to use assimilated stratospheric ozone from the DAO along with TOMS to generate the tropospheric ozone residual. Assimilation of ozone observations into a three-dimensional model provides another strategy for estimating tropospheric ozone. The DAO has already developed an ozone system to support the launch of the EOS Terra platform (Riishojgaard et al, 1999; Stajner et al., 1999). This system assimilates TOMS and SBUV observations and has undergone initial validation exercises including comparison with ozonesondes and HALOE observations. Figure 8a shows monthly averaged ozone from the assimilation analysis compared with independent HALOE observations. Given that the ozone assimilation provides global synoptic analyses, and a concurrent estimate of tropopause height, the product from the assimilation could be used to provide stratospheric profiles for residual calculation estimates of tropospheric ozone. Furthermore, the ozone assimilation does, in fact, provide a 3D field of ozone throughout the troposphere (Figure 8b). We propose to investigate the utility of the ozone assimilation to provide a tropospheric ozone product. In the near term we will more thoroughly analyze the existing product, comparing it with ozonesondes and Dobson measurements. We will determine whether or not the seasonal and geographic variability of the current tropospheric ozone is consistent with known tropospheric behavior, and we will test the sensitivity of the tropospheric ozone to assumptions in the assimilation process. In subsequent years we plan to determine which other types of ozone data are best added to the current system to improve the estimate of tropospheric products. At that time we would initiate the development of the error statistics and observation operators to assimilate the targeted new data type. (Candidates, SAGE, HALOE, MLS) Preliminary ozone assimilations have been performed using parameterized ozone chemistry. Our results will also be compared to limited estimates now being made from GOME observations under special conditions [Hoogen et al, 1999] and prepare us to work with ozone data from TES on EOS-CHEM

2.3.3-2 Use of the Combined Model to study tropospheric ozone

As shown by the observations of Langford [1999], the signature of STE should be apparent in the tropospheric ozone field. Thus our tropospheric ozone maps should (1) help quantify STE (2) allow us to validate the tropospheric chemical simulation. One interesting study will be to focus on the flux of ozone from the stratosphere to the troposphere during the Pinatubo and non-Pinatubo periods. The Combined Model will also be used to investigate the impact of STE on the tropospheric ozone budget. The first stage in this investigation is implementing the tropospheric chemistry package in an off-line mode. We then intend to look at STE events such as the transfer of stratospheric middleworld ozone into the troposphere by the monsoons. These events are ideal since they should have the greatest impact on the tropical tropospheric ozone amount - a region where data products are already being generated [Thompson and Hudson, 1999]. The experiments along these lines will parallel the aerosol experiments.

2.3.4 The impact of greenhouse gases on STE

Initial investigations of chemical changes in the stratosphere due to greenhouse gases have already been performed by our interactive 2D model [Rosenfield and Douglass, 1998]. However, the 2D model formulation is inadequate to represent the processes of STE because 2D stratospheric models do not correctly parameterize stratospheric middleworld dynamics [Schoeberl et al., 1998].

We intend to use the Combined Model to diagnose and simulate STE and the chemistry of the troposphere and stratosphere as discussed above. Next we plan to evaluate model capability, and perform a series of experiment to look at process sensitivities. For example, what is the model sensitivity to reduced planetary wave forcing or increased tropical heating? Finally we will simulate the variation in STE due to increasing greenhouse gases and then determine the kinds of feedbacks implied by alteration of the STE process. We anticipate having both the stratospheric and

tropospheric chemistry and aerosol packages running on-line with the GCM (using a reduced set of reactions or a parameterized chemical and aerosol production and loss schemes) as well as off-line for diagnostic calculations.

2.4 Data sets

This proposal involves the use of the multiple data sets, a large number of which are already available under the Science System (Table 1). Under this proposal we will maintain and update the Science System database. In addition, part of our proposed activity is to transfer the relevant EOS and other important data sets to the current science system. The most relevant data sets from the EOS platforms are listed in Table 2. Although the launch of EOS CHEM will not take place during the proposal period, we intend to continue to use UARS data and also utilize ENVISAT data (launch in November 2000) in this proposal. One important study we propose is the comparisons of ENVISAT data products with NASA satellite data products. The NASA data products we will use are UARS HALOE: O_3, H_2O, and NO_2; SAGE II/III: O_3, H_2O, and NO_2/ NO_3; Terra MOPITT: CO, CH_4; and TOMS, QuikTOMS: total ozone. The goal of the analysis will be to quantify the systematic differences between the data sets. Three of the ten ENVISAT instruments, SCIAMACHY, GOMOS and MIPAS will provide atmospheric constituent data similar to CLAES. ENVISAT should also provide the critical overlapping measurements needed to connect the UARS and EOS CHEM data sets.

The relevant ENVISAT instruments we intend to focus on are: GOMOS, a stellar occultation spectrometer which provides vertical profiles of NO_2, NO_3, O_2, H_2O, aerosols, and temperature from 15 km to 100 km with a vertical resolution of1.7 km. MIPAS; a limb viewing IR emission Michelson FTS which provides vertical profiles of temperature, O_3, H_2O, CH_4, N_2O from 5 km to 50 km, vertical resolution of 3 to 4 km. SCIAMACHY; a nadir/limb viewing UV/Vis/IR scanning spectrometer with lunar occultation capability. SCIAMACHY data processing has two levels, Near Real Time (NRT) and OFFLINE data processing. Most of the SCIAMACHY nadir products will be produced and distributed by ESA with a 3-4 hour delay. The limb viewing and occultation products will be produced and distributed by the German DLR/DFD with a longer time delay.

The ENVISAT data products, especially the SCIAMACHY limb and nadir ozone data products will be critical for the development of the tropospheric ozone data products described above since SCIAMACHY may provide a tropospheric ozone product (see Hoogen et al, 1999 for estimates of tropospheric ozone from an instrument similar to SCIAMACHY, GOME). Once the comparisons with other data sets are completed, the ENVISAT data will be used in this investigation. Table 3 lists the SCIAMACHY data product in more detail.

2.5 Correlative activities

Although the activities above will be the main focus of our investigations over the next three years, we also plan to improve and further develop the data analysis tools used by ourselves, the coordinated ACMAP and IDS, and the atmospheric community at large. These improvements are listed below:

1) Web page access to the Goddard Trajectory Model. A prototype page is already available at http://code916.gsfc.nasa.gov/EOS/restricted/traj_form.php3, username: Ertel, password: geostrophic . The new web page access will include access to diabatic trajectory calculations using the new fast trajectory model.

2) Improved radiative transfer model: The current radiative transfer model does not include the infrared heating due to the greenhouse gases CH_4 and N_2O. We plan to modify the current model or adopt a different model in order to allow for the absorption and emission by these gases. We also plan to improve the solar heating due to water vapor in the near infrared in order to better treat the absorption and multiple scattering due to aerosols.

3) Parallelized trajectory chemistry model. The trajectory model can be easily parallelized since individual parcels do not interact with their neighbors. We plan to develop a parallel version of the model that will allow rapid chemical integration of hundreds of thousands of parcels. Successful use of the trajectory model in a large scale, trace gas simulation mode has recently been demonstrated by Schoeberl and Morris [1999].

4) Continued Analysis of Aircraft/Balloon Mission data. As with the PIDS effort, we intend to apply our analysis tools to non-space observations. During this proposal time frame, we will be looking at SOLVE aircraft and balloon data. One of our current foci is the year to year variation in the descent of air within the polar vortex. This descent of air within the vortex has been documented using UARS HALOE observations (e.g. Schoeberl, et al., 1995) but has not been well validated from aircraft observations. We hope to use DC-8 lidar and microwave emission data from the ASUR instrument to get a better handle on the descent

3.0 Timeline and Expected Results

First proposal year:

Analysis of aerosol, chemical, and meteorological data for diagnosis of STE component processes.

Initial test runs with Combined Model - coupled with aerosols, tropospheric chemistry and stratospheric chemistry. Analysis of runs - comparison with observations using PDF techniques. Special simulations of NASA/NCAR model using artificial tracers.

Development of PV/PT tropospheric ozone product. Comparison to observations (e.g. SHADOZ and other sondes).

Analysis of Sage III Ozone Loss and Validation Experiment (SOLVE) observations.

Web page trajectory model interface complete, parallelization of trajectory chemistry model begins.

Second proposal year:

Pinatubo test run with Combined Stratosphere-Troposphere Model: Analysis of runs - comparison with Pinatubo aerosol observations from UARS and SAGE II with model results. Equivalent runs using parallel version of trajectory chemistry model begin.

Development of trajectory mapping tropospheric ozone product. Comparison to observations (e.g. SHADOZ and other sondes) to data product. More analysis of SOLVE observations - extend observations to SAGE III.

Third proposal year:

Long runs (20-50 year) with Combined model to assess impact of growth of greenhouse gases on STE and stratospheric chemistry. Analysis of results. Generation of daily tropospheric ozone product using trajectory mapping or assimilation methods. Analysis of SAGE III data.

4.0 Management Plan

The PI will manage the proposal. Since all but one of the co-investigators are on site at GSFC at least one day per week, we do not see any issues with travel. Monthly meetings will be used to coordinate overall activities. Steve Pawson will coordinate the modeling efforts. Rich Stolarski and Anne

Thompson will head the tropospheric ozone effort. Specific task/ responsibilities for the co-investigators are given below:

Schoeberl - overall lead and responsible for trajectory model.

Model development group
Pawson -Coordinate the development of the combined stratospheric/ troposphere model
Chin- Tropospheric chemistry model (GOCART) and sulfur chemistry packages.
Considine - Pinatobo aerosol experiments using combined model and interactive 2D model.
Douglass - Stratospheric CTM and data analysis.
Ginoux - Tropospheric and stratospheric aerosol simulations.
Kawa - Stratospheric chemistry module, analysis of chemical model results.
Lin - Improvements and changes in NASA/NCAR model.
Rosenfield - Improvements to radiation model and greenhouse gas experiments with coupled model.
Toon - Aerosol microphysics module.

Model and data analysis and validation group
Stolarski and Thompson - Coordinate the development of the ozone data product..
Dessler - Tropical upper tropospheric processes and water vapor..
Gleason - ENVISAT and GOME data analysis.
Hollandsworth - Development of tropospheric ozone product.
Lait - Management of science system, data ingest, satellite and aircraft data analysis.
Morris - Trajectory mapping of SAGE III and other data sets for use in tropospheric ozone product.
Newman - Analysis of aircraft and TOMS data, analysis of dynamics in the NASA/NCAR GCM.
Sparling - Statistical analysis of model results and EOS data sets.

Programming Support (2 MY): Maintenance and development of the Combined Model, maintenance of the Science System, transfer of EOS and other data sets to the Science System.

5.0 Personnel

Vitae are attached.

6.0 Facilities and Equipment

Most of the data analysis and research will be carried out on the Code 916 workstation cluster. This system consists of 42 SGI workstations and roughly a terabyte of attached disk space. The science system allows any user within the cluster to transparently access any data file. One workstation has been assigned the task of running the GSFC trajectory model for outside users. The science system also includes a video recorder system for animations and a number of color and laser printers. Upgrades to the system under our cost plan include upgrades to the core processor chips in the SGI's (from R10K to R12K) and acquisition of additional RAID disk systems to archive the satellite data sets. The 9 gigabyte SA RAIDS will be replaced with 32 gigabyte SX systems on an ongoing basis.

Our upgrade plan is as follows

2000 - Replace one Power Challenge data server with an Origin 2000 in order to analyze the results of the model and replace one SA RAID disks with an SX RAID disk for data storage. SX Raid Disks have 3x the capacity of the SA RAID disks	$112K
2001 - Replace two SA RAID disks with SX RAID Disks	$60K
2002 - Replace two Indigo^2 with SGI Octanes	$50K

Combined Model calculations will be carried out on the Data Assimilation Office computer systems at no charge to the proposal. The results will be transferred to the Science System for analysis by the investigators.

7.0 Current Support

The principal investigator is a civil servant and NASA covers costs. The principal investigator is also PI of a proposal funded under the AEAP program.

8.0 IDS Proposal Budget Breakdown

FY				2000	2001	2002
	Name	FTE	Cost/FTE			
Non-Civil Servant						
	Mian Chin	0.25	$120,000	$30,000	$31,500	$33,075
	Joan Rosenfield	0.9	$144,000	$129,600	$136,080	$142,884
	Leslie Lait	0.25	$110,000	$27,500	$28,875	$30,319
	Lynn Sparling	0.5	$109,000	$54,500	$57,225	$60,086
	Andy Dessler	0.1	$125,000	$12,500	$13,125	$13,781
	Paul Ginoux	0.1	$82,000	$8,200	$8,610	$9,041
	Programmer #1	1	$100,000	$100,000	$105,000	$110,250
	Programmer #2	1	$80,000	$80,000	$84,000	$88,200
	Stacy Hollandsworth	0.5	$77,000	$38,500	$40,425	$42,446
	Gary Morris			$20,000	$20,000	$20,000
	David Considine	0.2	$125,000	$25,000	$26,250	$27,563
	Subtotal	**4.8**		$525,800	$551,090	$577,645
Civil Servant						
	Mark Schoeberl	0.3				
	Anne Douglass	0.25				
	S. R. Kawa	0.3				
	Richard Stolarski	0.2				
	Paul Newman	0.2				
	Ricchard Rood	0.1				
	James Gleason	0.1				
	S. J. Lin	0.2				
	Anne Thompson	0.1				
	Subtotal	**1.75**				
Non-funded CoI's						
	Steven Pawson	0.25	(Funded by DAO)			
	O. B. Toon	0.1	(Collaborative Investigator)			
MPS Rate				$12,000	$13,500	$15,500
			Actual FTE*			
MPS	Total FTE	6.9	5.4	$64,800	$72,900	$83,700
Equipment				$112,000	$60,000	$50,000
Supplies	(Furnished by Branch Assessments)			$0	$0	$0
Travel	$ 2,000	(per Contractor FTE)		$9,600	$9,600	$9,600
Publicatons	$ 2,000	(per Total FTE)		$13,800	$13,800	$13,800
Subtotal				$726,000	$707,390	$734,745
Branch (4%) +Division (3%) Assessments		7%		$54,645	$53,244	$55,303
			Total	**$780,645**	**$760,634**	**$790,048**

* FTE's not under NAS5-XXXXX contracts removed:
Sparling, Considine, Dessler, Chin, Ginoux

Appendix A Brief Summary of the Previous IDS

This section describes some of the current research activities under the PIDS investigation. Reports of PIDS activities through 1997 can be found at http://hyperion.gsfc.nasa.gov/EOS/EOS.html. This section also describes some of the modeling and data analysis tools that we intend to use in this investigation.

Roughly 30 papers funded or partially funded under the PIDS have been published since the 1997 report. We also have filled 15,984 no-cost requests from our automailer system for the fiscal year October 1997 to October 1998. Of those requests, 2,963 requests were for trajectory calculations. The PIDS has also supported the EOS Project by providing specialized calculations associated with the EOS instruments, the most recent of which is the HIRDLS resolution study (Lait, 1999). The PIDS has also provided project scientists for the EOS CHEM mission. The PI also served as first head of the EOS Atmospheres Panel, and headed chemistry group for the EOS follow on mission meeting at Easton.

A.1 Models

The PIDS has developed an interactive 2D model, and co-funded the development of the 2D, 3D model and chemistry packages.

A.1.1 The interactive 2D model

The interactive 2D model was developed to study the radiative-dynamical feedbacks between changes in ozone, aerosols and water vapor and the stratospheric circulation (Bacmeister et al., 1995). The 2D approach was used because of the computational cost of a fully 3D calculation. It now appears possible to use a fully 3D model for a limited number of these assessments, as will be discussed below; however, the interactive 2D model remains a useful tool for estimating the magnitude and importance of feedbacks.

The interactive 2D model was used to study the stratospheric effects of the Mount Pinatubo aerosol cloud. The computed tropical ozone column losses of 2-3% and stratospheric warming of 2-3 K in good agreement with observations [Rosenfield et al., 1997]. The prediction of lower stratospheric chlorine partitioning was also in good agreement with UARS data [Dessler et al., 1997]. The 2D model has also been used to study the radiative impact of subvisible cirrus clouds Rosenfield et al., [1998] found that the resulting tropopause warming was shown to lead to as much as 1 ppmv more water vapor reaching the stratosphere. More recently, the interactive 2D model has been used to investigate the chemical and dynamical effects of increasing CO_2. In Rosenfield and Douglass [1998] it was shown that the stratospheric cooling resulting from doubling CO_2, while keeping all other boundary conditions fixed, led to an increase in ozone. This increase was due in part to a decrease in reactive nitrogen (NO_y), which participates in an important catalytic ozone destruction cycle. Figure A.1.1-1 shows the computed recovery of globally averaged ozone between 60S and 60N due to the reduction of the chlorine loading of the stratosphere. The computed 2050 ozone amounts are greater with increasing CO_2 than with fixed CO_2, indicating that the ozone layer will recover sooner than predicted by many current models, which do not allow for the feedbacks due to changing CO_2. This result is opposite of that obtained by Shindell et al. [1998], whose study focused on the polar regions and the effects of heterogeneous reactions.

A.1.2 The 3D Chemical model

The 3D chemical model, developed within ACMAP and augmented by the PIDS, has been used to diagnose the DAO assimilation system and investigate chemical processes in the stratosphere

[Douglass et al., 1996]. Simulations using the 3D chemistry and transport model (CTM) have been compared with observations as part of an overall evaluation of the transport produced by DAO wind fields [Douglass et al., 1996; 1997; 1999]. Where it is possible to use the model and DAO winds to account for the contribution from transport, the CTM has been used to investigate chemical processes of the stratosphere. These include reformation of chlorine reservoir species (Douglass and Kawa, 1999), and the late spring recovery of southern hemisphere polar ozone (Pierson et al., 1999).

The chemistry package developed for the 3D chemistry model was used with the trajectory model to examine the development of the Antarctic ozone hole (Schoeberl et al., 1995) and to examine the cause of the low ozone pockets reported by Manney et al. (1995) (Morris et al., 1998).

A.2 Data Analysis Tools

The PIDS focused on stratospheric processes, analyzing data from UARS (e.g. Douglass et al., 1995, Schoeberl et al., 1995) as well as aircraft data (e.g. Newman et al., 1996). As part of the data analysis effort, the PIDS developed new and important tools that allowed data sets to be analyzed in new ways. These tools are summarized briefly below:

A.2.1 PV/PT mapping and the trajectory model

The PIDS pioneered the use of potential vorticity/potential temperature (PV/PT) coordinate transforms to remove meteorological variability from trace gas data [Schoeberl and Lait,, 1992]. This technique, most applicable to mid and high latitude trace gas analysis is now widely used to both analyze data and initialize 3D models from climatological data. The PV/PT mapping technique has most recently been used to improve the climatology of ozone for SBUV retrievals. With the technique, SAGE II data are binned into PV/PT coordinates on a monthly basis. Then using the daily PV/PT maps, the stratospheric ozone field can be reconstructed to be used as a first guess field in the SBUV retrievals. We have found that PV/PT reconstruction works best during fall, winter and spring periods in the extra tropics. In the summer, and in the tropics, the PV fields are too uncertain for the method to be reliable.

The PIDS also developed the GSFC trajectory model [Schoeberl and Sparling, 1995] that has been widely used by the research community. Specific trajectory model calculations can be made by and are freely available to all researchers via the "auto-mailer." system. The GSFC trajectory model has developed a world wide following and a UNIX workstation is dedicated to running the model for other investigators. The GSFC trajectory model has also been used as a diagnostic tool in a large number of investigations (e. g. Kawa et al., 1997 and others). The advantage of the GSFC trajectory model over other models is its flexibility, ease of use and ability to select from a wide variety of dynamical data sets. The GSFC trajectory model has been recently re-engineered to speed up diabatic integration. The new model is 20-50 times faster than the old version for diabatic cases. This allows us to perform ensemble experiments using a large number of parcels run for a long period of time. We have recently improved the tropospheric transport code to account for the situation when isentropic surfaces intercept the ground, and we have included latent heating. The trajectory formalism is based upon conservation of potential temperature,
$\frac{\partial \Theta}{\partial t} + u\frac{\partial \Theta}{\partial x} + v\frac{\partial \Theta}{\partial y} + w\frac{\partial \Theta}{\partial z} = Q$ where the notation has its usual meaning (e.g. Θ is potential temperature and Q is diabatic heating). For transport of parcels by u and v winds, we rewrite the above $\frac{D\Theta}{Dt}_{H} = Q - w\frac{\partial \Theta}{\partial z}$. In the stratosphere, the last term is usually neglected, but it cannot be neglected in the troposphere where a substantial amount of heat is transported upward by convection (divergent

processes) . We are currently extending the trajectory model formalism to include the convective heat transport effect.

A powerful application of the trajectory model developed by the PIDS is “trajectory mapping” [Morris et al., 1995]. In trajectory mapping, the trajectory model initiates parcels at measurement locations. These parcels are then moved by the analyzed winds to other measurement locations which allow indirect comparison. The trajectory mapping method can thus be used to compare measurements taken at different locations and times. Recently, we have used trajectory mapping to compare SAGE II and UARS HALOE ozone measurements. Preliminary results suggest a drift of -1 to -3%/yr of HALOE relative to SAGE below 25 km and about +1%/yr above 25 km. These drifts are larger than the ozone trends reported by either instrument over that period.

Long term, diabatic trajectory calculations have also been used to investigate the dispersion and transport of stratospheric trace gases and age-of-air. We have recently shown [Schoeberl et al., 1998] that the decay time for gases released into the middle and upper stratosphere (overworld) is about a year, but the lower stratospheric middleworld decay time is months. This result has been extended to an assessment of the transport of aircraft exhaust release [Schoeberl and Morris, 1999].

Age-of-air has emerged as one of the key diagnostics of transport (Hall and Plumb, 1994, Hall and Waugh, 1997). However, the theory of connecting age-of-air to tracer measurements has been developed only for inert tracers with known time dependencies. Recent Schoeberl et al. [1999] have generalized the age spectrum concept to include photochemically active tracers. This work shows how multiple measurements of photochemically active tracers can be used to untangle the age spectrum for a tracer sample. This kind of diagnostic will be useful in both tropospheric and stratospheric studies - both models and observations.

A.2.2 Statistical methods for data analysis

Most recently the PIDS has pioneered the use of PDF (probability distribution function) statistical techniques in data analysis [Sparling, 1999]. The PDF techniques combined with the techniques described above provide a new approach to data and model analysis as demonstrated in analysis of SONEX data (Thompson et al., 1999). One important result that has recently been obtained using the PDF method is the preliminary derivation of the dissipation scale from the high horizontal resolution, aircraft trace gas data. Most recently the PIDS has developed innovative statistical approaches to large scale tracer transport through the use of PDFs of satellite observations and model fields (Sparling, 1999). These methods are a promising new way to synthesize both tracer and dynamical variability and its global time evolution. A recent investigation of small scale variability has used two-point PDFs in the analysis of high resolution, aircraft trace gas data. An important preliminary result is the development of a method for inferring the horizontal dissipation scale from the statistical properties of the variability.

The transition region that encloses the tropopause is a region in which air with chemical properties of the stratosphere and troposphere are being mixed together (e.g. Folkins et al., 1999). Thus, one expects that there are statistical signatures of this mixing, and thus of the underlying dynamics of STE. These signatures will be investigated using a the statistical methods that have been developed under the PIDS. Several of these methods are tailored specifically to the analysis of variability in transition regions of the atmosphere (Sparling, 1999).

We propose a comprehensive statistical study of ozone, water vapor and temperature that is based on satellite, aircraft and balloon measurements of the tropopause region. Conditional one-point PDFs of the satellite measurements will be computed, conditioned on season, potential temperature, longitude, latitude, or tracer concentrations. PDFs for mid-latitude fields will also be conditioned on meteorological fields such as PV, and in the tropics static stability. Two-point PDFs of the in situ

data will give information about small scale mixing processes near the tropopause. The work proposed here will directly benefit from the work proposed under the Sparling (ACMAP) proposal (Appendix B) in which many of the fundamental ideas and tools will be developed.

A.3 The Science System

A vast amount of data from satellite, ground-based, and aircraft instruments is needed to carry out the interdisciplinary analysis and comparisons being proposed. Even with the development of the Distributed Active Archive Centers (DAACs), these locally resident data collections must be organized and managed effectively.

Under the PIDS, we developed a data system which organizes data, software, and documentation. Designed around a collection of Unix workstations and servers which share files among each other, this "Science System" encourages collaboration by putting a wide variety of data sets, and the software to read the data, into transparent locations that are accessible to anyone. Most of the data follow a standardized naming convention and are written in a compact, platform-independent, self-documenting format. Table 1 lists some of the data sets that are available on the Science System.

In addition to the data reader subroutines, an extensive IDL toolkit of routines for modeling, analysis, and plotting have been developed by the system's users and made available to all. The open source programming codes can be modified or improved by any user (under a revision control system); all changes are promulgated to all computers in our data system, so that everyone uses the same version of the software.

As the number and size of the data sets have grown, performance demands have increased. New computer servers and upgrades to existing machines will be needed. In addition, a significant bottleneck has developed in simply looking up what data are available. Under this IDS, programming support will be used to install and configure new database software to help manage the data access.

Appendix B Related IDS and ACMAP Proposals

Proposals being coordinated with this IDS are listed below. Each of the efforts will accelerate the progress of this IDS, but our IDS is not totally dependent on the existence of the other efforts. Figure B-1 shows the interrelationship between proposals at a glance.

M. Chin (ACMAP):Aerosols, Chemistry, and Radiative Forcing: A 3-D Model Analysis of Satellite and ACE-Asia Data

This project is to incorporate a global 3-D model and satellite data into the Aerosol Characterization Experiment - Asia (ACE-Asia) field mission. The objectives are (1) to determine the physical, chemical, and optical properties of the multi-component aerosol and the processes that control these properties; (2) to investigate the interactions between aerosols and tropospheric chemistry; and (3) to assess the aerosol radiative forcing over the Asian-Pacific region.

(This proposal is linked through the tropospheric chemistry and aerosol processes models discussed below.)

A. Dessler (IDS): Investigations of the tropical tropopause region

This proposal investigates the tropical tropopause region (TTR), that volume of the atmosphere extending from about 25°S to 25°N and from approximately 200 hPa (~12 km) to 50 hPa (~20 km). Mass entering the stratosphere must transit this region, and processes occurring here primarily set the abundance of water vapor in the stratosphere. In addition, the cold temperatures in this region (T <

200 K) make the abundance of greenhouse gases in this region (e.g., water vapor or ozone) and the response of their abundances to global change scenarios important.

(This proposal is will focus more on the tropical upwelling processes and the results should help us validate the processes of tropical STE within our model.)

A. Douglass (ACMAP): Continued Funding of the Stratospheric General Circulation with Chemistry Project

This proposal utilizes the CTM with winds and temperatures from the DAO to interpret observations of ozone and other stratospheric constituents from various platforms, including satellite, aircraft, and balloon. Work is focussed on evaluation of transport and photochemical processes which are key to the ability to produce realistic assessment of the impact of anthropogenic and man-made perturbations. Priorities include: Resolving inconsistencies in modeled NO_y and O_3 distributions in the lower stratosphere; establishing the relative importance of horizontal and vertical transport to the composition of the lowermost stratosphere with the goal of developing the capability to model the flux of stratospheric constituents such as O_3 to the upper troposphere.

(This proposal is linked through the stratospheric chemistry and transport models discussed below.)

P. Newman (ACMAP): Continued Funding for Analysis of Spatial and Temporal Variability of Stratospheric Dynamics and Trace Constituents

This proposal is to use data assimilation data sets (DAO, NCEP/NCAR, UKMO, and NCEP/CPC) covering the last two decades to investigate how planetary wave driving of the stratosphere is connected to polar stratosphere, and to determine the response of the NASA/NCAR GCM to the heating of the tropical upper troposphere in the double 2xCO2 atmosphere. This proposal will focus on the changes of linear wave propagation in the stratosphere under a 2xCO2 environment.

(This proposal will be providing diagnostic analysis of the NASA/NCAR GCM.)

A. Da Silva (IDS): An Interactive Retrieval/Assimilation System for Atmospheric Aerosol

This proposal combines the advances in remote sensing of atmospheric aerosols, aerosol modeling and data assimilation methodology to produce high spatial and temporal resolution 3D aerosol fields, and to assess the impact of these fields on climate modeling and more generally on atmospheric climate assimilation.

(This proposal is linked through aerosol processes.)

L. Sparling (ACMAP): An investigation of the statistical properties of sub-grid scale variability in chemical tracers in the UT/LS: Applications to chemical modeling, data validation and constituent data assimilation

This proposal is to use a combination of aircraft and balloon data collected over the past decade to develop a statistical synthesis of sub-grid scale variability in chemical tracers. The research includes an investigation of fundamental problems related to sub-grid scale transport and chemical mix-down. The results of this research are directly applicable a number of practical problems in the areas of model evaluation, satellite data validation and constituent data assimilation.

(This proposal is will help us understand the role of sub-grid scale mixing and effective parameterization of that processes within the Combined Model.)

A. Thompson (ACMAP) - Climatological and Process Studies of Tropical Tropospheric Ozone using Ozonesonde and Satellite Data

This proposal focuses on: (1) climatology of southern hemisphere tropospheric ozone at tropical and subtropical stations; (2) refinement of modified-residual TTO data, using 1997-1999 ozonesonde data; (3) analysis of ozone data over southern Africa and the adjacent oceans, including profiles collected during the R/V R H Brown 1999 Aerosols and INDOEX cruises. In conjunction with ACMAP funding to R D Hudson at U MD, modified-residual maps of tropical tropospheric ozone are produced under this support.

(This proposal is will provide tropospheric ozone estimates for validation of our data product.)

Steven Pawson (ACMAP)- Reanalysis for Stratospheric Trace Gas Studies

In this proposal, a 4-year reanalysis (May 1991--April 1995) of the troposphere and stratosphere will be undertaken and evaluated. Particular attention will be given to the radiative consistency of the assimilated data, with the inclusion of lower stratospheric volcanic aerosols and assimilated ozone data in the assimilation system. The sensitivity to input data sets will be studied, using temperatures obtained from TOVS satellites and UARS-based limb-sounding instruments. The main reason for this exercise is to provide a stable data set for trace gas transport studies; therefore, a thorough evaluation of the transport characteristics of the assimilated data will be made.

(This proposal will provide re-assimilated wind and temperature fields over the UARS and Pinatubo period.

O B. Toon (IDS): Numerical simulations of atmospheric aerosols to aid in the interpretation of EOS data

This proposal covers the modeling of tropospheric aerosols and stratospheric aerosols and application of these models to the interpretation of EOS data, which will allow us to better understand problems of importance in the Earth's radiation budget, climate, and atmospheric chemistry.

(This proposal is will provide improved aerosol microphysics modeling.)

Appendix C Combined Model component descriptions and proposed developments

C.1 Dynamical Model

The new joint NASA/NCAR model will be used as the base circulation model for this investigation. The dynamical core is based on the work of Lin (1997) in which the `finite-volume semi-Lagrangian' technique used in the model was developed. The model uses a regular latitude-longitude grid with Lagrangian vertical coordinate. Re-mapping of meteorological variables to a hybrid vertical grid is performed at regular intervals (currently 30 minutes) when the physical tendencies are recalculated. The model currently uses the complete NCAR CCM3 physics package (representing radiative transfer, clouds and the hydrological cycle, and turbulent exchange of moisture and momentum with the surface). As part of the model development at NCAR, the physical parameterizations are being updated, and a version of the CCM4 physics should soon be implemented. Multi-year simulations with the model have been made as part of the validation effort. Most of these (20-year integrations) are performed with a horizontal resolution of 2 degree latitude by 2.5 degrees longitude, which is comparable to the higher-resolution models participating in the Atmospheric Model Intercomparison Project (AMIP, Gates et al. 1999), and with 55 levels, which is at the high-end of the models in the GCM-Reality Intercomparison Project for SPARC (GRIPS, Pawson et al. 1999). The resolution of the NASA/NCAR GCM is flexible (it has been run with homogeneous 0.5-degree horizontal resolution for shorter periods) and can be adapted to the requirements of the problem.

GRIPS model reveals that this model always lies amongst the "best" in comparisons with other models and observations. As an example, Figure C.1-1 shows the long term mean temperature at 100 hPa in January. The model lies very close to the best observational estimates. The accurate NASA/NCAR dynamical core is ideally suited to atmospheric transport calculations. Several highly parameterized, non-interacting trace gases have already been included. Fig. C.1-2 shows zonal mean methane for Jan. 1980, one year after initialization of an on-line simulation. The most important features of the atmosphere are captured: a tropical peak with relatively sharp meridional gradients - although these are weaker than observed. Data from a single day (Fig. C.1-3) shows features associated with the polar vortex structure the subtropical barriers and breaking planetary waves.

C.2 Stratospheric Chemical Model

The stratospheric chemical model, which combines advection and photochemical algorithms, is described in detail in Douglass and Kawa [1999]. Briefly, the advection scheme [Lin and Rood, 1996] calculates constituent transport on a 2.5 x 2 lon-lat grid, with 28 vertical levels using a hybrid sigma coordinate for 10 tropospheric levels and pressure for 17 stratospheric levels. The spacing is about 1 km near the tropopause and increases to 4 km near the upper boundary. This scheme maintains sharp gradients and appropriate correlations for long-lived constituents. The photochemical scheme contains all gas phase and heterogeneous reactions thought to be important in the stratosphere; input data for reaction rates are taken from the current JPL evaluation [DeMore et al., 1997]. The photolysis rates are calculated using temperature dependent cross sections [DeMore et al., 1997] and reduced fluxes interpolated from a table lookup based on the detailed radiative transfer calculations from the model of Anderson and Lloyd [1990]. The photolysis rates calculated in this way compare favorably with the photolysis benchmark which was developed as part of the AEAP program [Stolarski et al., 1995]. This photochemical scheme is used in the CTM and also in the trajectory photochemical model. The approach of using assimilated winds and temperatures in an off line chemistry and transport model has been used by ourselves and others in analysis of observations from aircraft (e.g., Douglass et al., 1991; Lefevre et al., 1994); balloon (e.g., Kondo et al., 1996); ozonesonde (e.g., Weaver et al, 1999); and satellites included Nimbus 7 TOMS (e.g., Douglass et al., 1996; Jiang et al., 1998), UARS (e.g., Chipperfield et al., 1996; Douglass and Kawa, 1999), and POAM (Deniel et al., 1998).

C.3 Tropospheric Chemical Model

The current GOCART model includes modules of advection, convection, diffusion, emission, chemistry, dry and wet depositions for aerosols. The model has the same horizontal resolution as the stratospheric model (C.2), but with lower vertical resolution in the stratosphere and higher in the troposphere than the stratospheric model. Typically, the model contains 15 (using GEOS DAS version 1, or GEOS-1) to 29 (GEOS-2) vertical sigma levels in the troposphere. We are now in the process of implementing a full tropospheric chemistry module into the GOCART model. Two types of chemical solvers are going to be used: a highly accurate sparse-matrix vectorized Gear solver (SMVGEAR) [Jacobson and Turco, 1994; Jacobson, 1998], and/or a fast (typically 10 times faster than SMVGEAR) but sufficiently accurate family type solver [Zhao et al., 1999]. In the meantime, we will also incorporate emission modules for ozone precursors, such as CO, NOx, natural and anthropogenic hydrocarbons, using the most recent global emission inventory data bases (e.g., GEIA, EDGAR).

C.4 Radiative Transfer Model

The current radiation model is as described in Rosenfield et al. [1994] with the addition of an infrared transmission parameterization which allows for varying amounts of CO_2 [Chou and Kouvaris, 1991]. It is used in the 2D interactive model and as a standalone code to compute daily 3D heating rate fields from analyzed temperatures. These are the heating rates that are used in the diabatic trajectory

calculations discussed in Appendix A.2.1. The shortwave absorbers are O_3, H_2O, and CO_2, and the longwave absorbers are CO_2, O_3, and H_2O. A shortcoming of the current longwave scheme is that it does not include the infrared window region absorption of the minor trace gases N_2O, CH_4, and CFCs. The band structure of the longwave code, i.e. four broad bands, makes it difficult to include these additional absorbers. We plan to examine the Chou-Suarez code [Chou and Suarez, 1994], which has an expanded number of broad bands, for possible use. This code has been updated to include the minor trace gases [Kratz et al., 1998]. It does not include, however, the 14 micron band of ozone. Shine et al. [1995] have shown that this band of ozone makes a large contribution (30%) to the total infrared radiative forcing due to stratospheric ozone perturbations. We plan to add this absorption to the Chou-Suarez model, if it is adopted, as an option to be used for ozone perturbation studies.

The solar heating due to water vapor in the near infrared is calculated in the current model by a modification of the Lacis and Hansen [1974] parameterization, which treats the entire 0.7-4.0 micron region as one wide band. The absorption and scattering of aerosols in this band is treated using a k distribution method. We plan to update the near infrared solar heating by using a parameterization with a number of narrower bands in this spectral region, in order to improve the treatment of aerosols. A parameterization under consideration is that of Chou and Lee [1996]. These improvements will hopefully improve the problem of the mass imbalance in the lower stratosphere where the net heating is a small residual of the short wave and long wave heating rates.

C.5 The Aerosol Model

C.5.1 The GOCART microphysics and aerosol model

The current GOCART model simulates four major tropospheric aerosol species (sulfate, dust, sea salt, and carbonaceous). The model includes a number of discrete size bins of dust and sea salt aerosols (1 sub-micron bin and 3 super micron bins), which are originated from their wind-speed-dependent emissions. For sulfate and carbonaceous aerosols, we have been calculating their mass without resolving their sizes. Figure C.5.1-1a,b shows a comparison of the results of the model with TOMS and Aeronet data. We will adapt the microphysical model of Toon [1988] (C.5.2) in conjunction with the GOCART model for size resolved multi-component aerosol simulations. Depending on the computational limitation, we may have to modify the Toon model in order to conduct efficient global simulations.

C.5.2 The Toon aerosol model

The basic Toon microphysical model is described by Toon et al. (1988). Standard versions of the model are maintained at NASA Ames Research Center. A wide community of users works with this code and continue to improve it.

The Toon model has been used for one-dimensional studies of: chemistry in the marine troposphere (Toon et al., 1987); the Pinatubo volcanic cloud (Zhao, Turco and Toon, 1995); polar stratospheric clouds (Toon et al., 1989); cirrus clouds (Jensen et al., 1994a,b); marine stratus clouds (Ackerman, Toon and Hobbs, 1993, 1994, 1995a,b). The model has also been used for three-dimensional simulations of: wind-blown Saharan dust in conjunction with the grid point NCAR/Penn State mesoscale model (Westphal et al.,1987,1988); biomass combustion smoke in conjunction with the NCAR/Penn State mesoscale model (Westphal and Toon, 1991a,b). Most recently the model has been adapted it to the NCAR MATCH model which is a grid point version of the NCAR Community Climate model physics package and analyzed winds. The model is highly flexible and can treat a very wide variety of chemical and aerosol systems.

The current Toon model treats all of the basic physical and chemical process that affect aerosols and clouds. The model is configured so that the particle size range covered is variable, the number of

different types of aerosols included is variable, the resolution of the size distribution is variable, the geometry of the spatial grid is variable and the time step is variable. All of these features are essential to an adequate treatment of the physics and chemistry of the aerosols, while keeping computer resources within control. Each type of aerosol requires a different approach to computational efficiency while accurately simulating the optical properties of the aerosols, as discussed in detail below. The Toon model also is capable of being partitioned to simulate the aerosols in a particular region. Due to the short lifetimes of most tropospheric aerosols the ones that originate from a specific source or event often do not travel far. Hence, in comparing with an EOS observation of an event, we can isolate a portion of the world in which the aerosol involved is most prevalent.

Within the proposal time frame we will compare the results of the two microphysical models (GOCART and Toon) to improve the parameterization of aerosols within the both the GOCART model.

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Tables

Table 1 Data Sets Archived in the Science System

Data Type	Mission
Satellite	UARS (HALOE, CLAES, MLS, HRDI, ISAMS), POAM, SAGE, SBUV, TOMS, ADEOS, CRISTA
Aircraft	STEP,AAOE, AASE I, AASE II, SPADE, STRAT, TOTE/VOTE, POLARIS, SUCCESS, SONEX, WAM, ACCENT
Ground, Balloon	NDSC, Rawinsondes, POLARIS
Meteorological Data	NCEP Analysis (1979-), NMC Re Analysis (1955-), UKMO (1991-), DA (various versions) (1991-)
Model Calculations	Diabatic heating rates for the Meteorological analysis, 2 years of CTM ru (1995-1996, 1997- 1998)

Table 2. New data sets to be used under this proposal

EOS Data Set Available within t next 3 years	Usage under this proposal
AIRS	More precise measurements of the temperature of the lower stratosphere and upper troposphere to estimate the cross tropopause mass flux, also upper tropospheric and lower stratospheric ozone
MOPITT	CO Measurements as tracers of upper tropospheric circulation and as indicator (along with TOMS aerosols) of biogenic aerosols
MISR	Aerosol information to be used in conjunction with TOMS
TOMS & Quick TOMS and TRIANA	Tropospheric aerosols, column ozone (and column SO_2 . The SO2 will be used volcanic aerosol studies. The column ozone will be used in computing the tropospheric residual. The TRIANA O_3 data will be useful for the study of mesoscale events because of the higher time resolution
SAGE III	Stratospheric ozone and aerosol profiles. The ozone data is to be used with TOMS data to compute the ozone residual
GLAS	Tropospheric aerosol, SVC and cloud height distribution
DAO Assimilation	Drives transport models and trajectory models

Table 3. SCIAMACHY data products.

	NADIR			Limb/Occultation		
Type	UV/Vis	IR	UV/Vis IR	UV/Vis	IR	UV/Vis/IR
NRT	O_3, NO_2, SO OClO*, H_2C	H_2O, CO, N CH_4	Clouds, Aerosols			
OFFLINE	O_3, NO_2, BF SO_2*, OClO H_2CO*	H_2O, CO, C N_2O, CH_4, F	Clouds, Aerosols	O_3, NO_2, Br	H_2O, CO, C N_2O, CH_4, F	Aerosols
(*) These molecules can only be detected under special conditions						

Figure Captions

Figure 1 Middleworld and overworld regions of the atmosphere overlaid on the zonal mean temperature field for January 2, 1995. Hoskins [1991] introduced the terms middleworld and overworld. UK Met Office Stratospheric Assimilation data set was used. The black arrows denote exchange and transport. Thin black line show the 380 (dotted), 355 and 310K isentropes. Pink lines show mixing. The tropopause is orange

The Lower Stratosphere and Troposphere

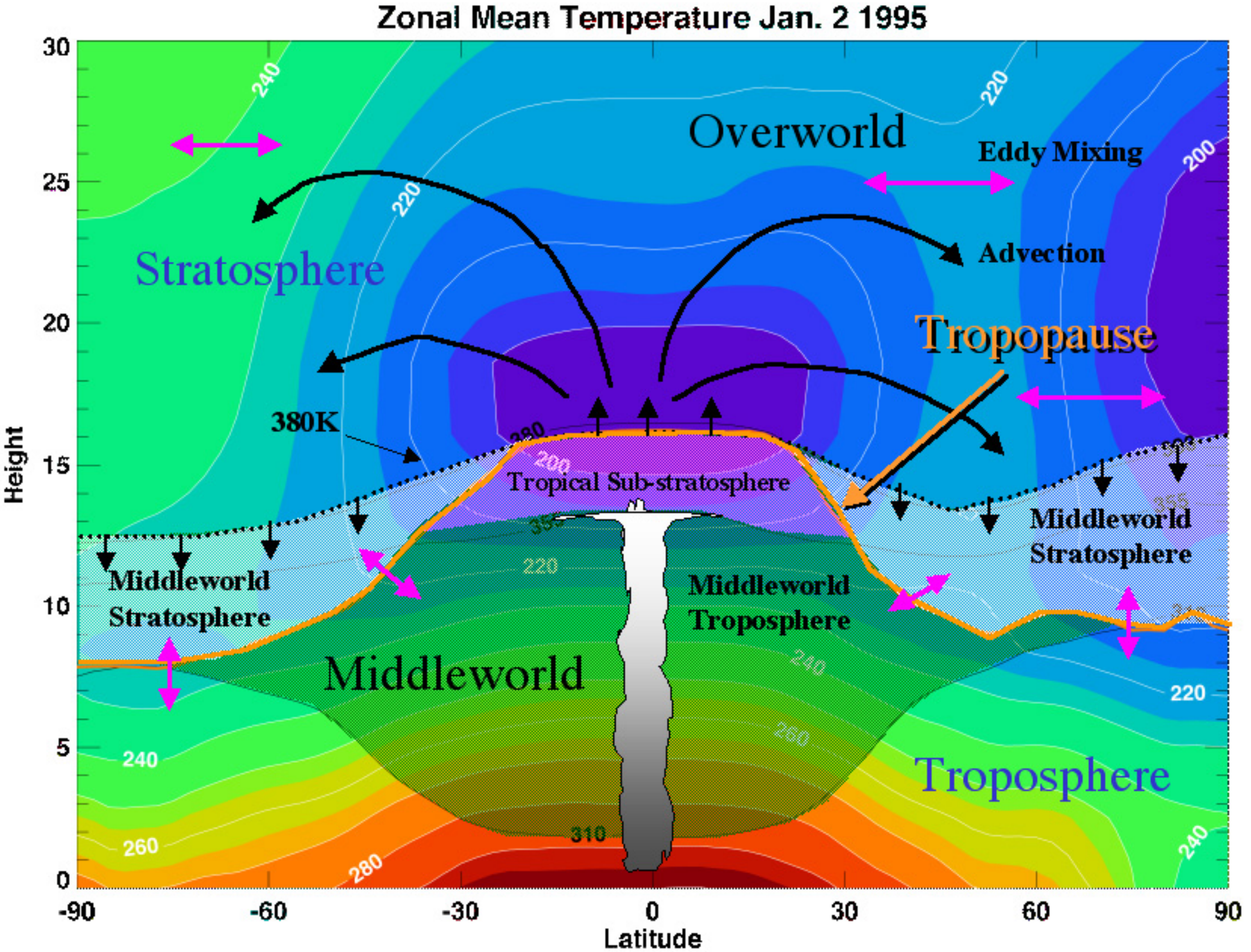


Figure 2. Ozone, water and temperature measurements made during an December 11, 1996 ER-2 dive at the equator during the STRAT mission. Note the rise in ozone below the tropopause and the complex structure of water vapor. The increase in ozone suggests downward mixing from the tropopause. The regions between 360K and tropical tropopause is sometimes called the tropical sub-stratosphere. These results agree with those of Folkins et al. [1999].

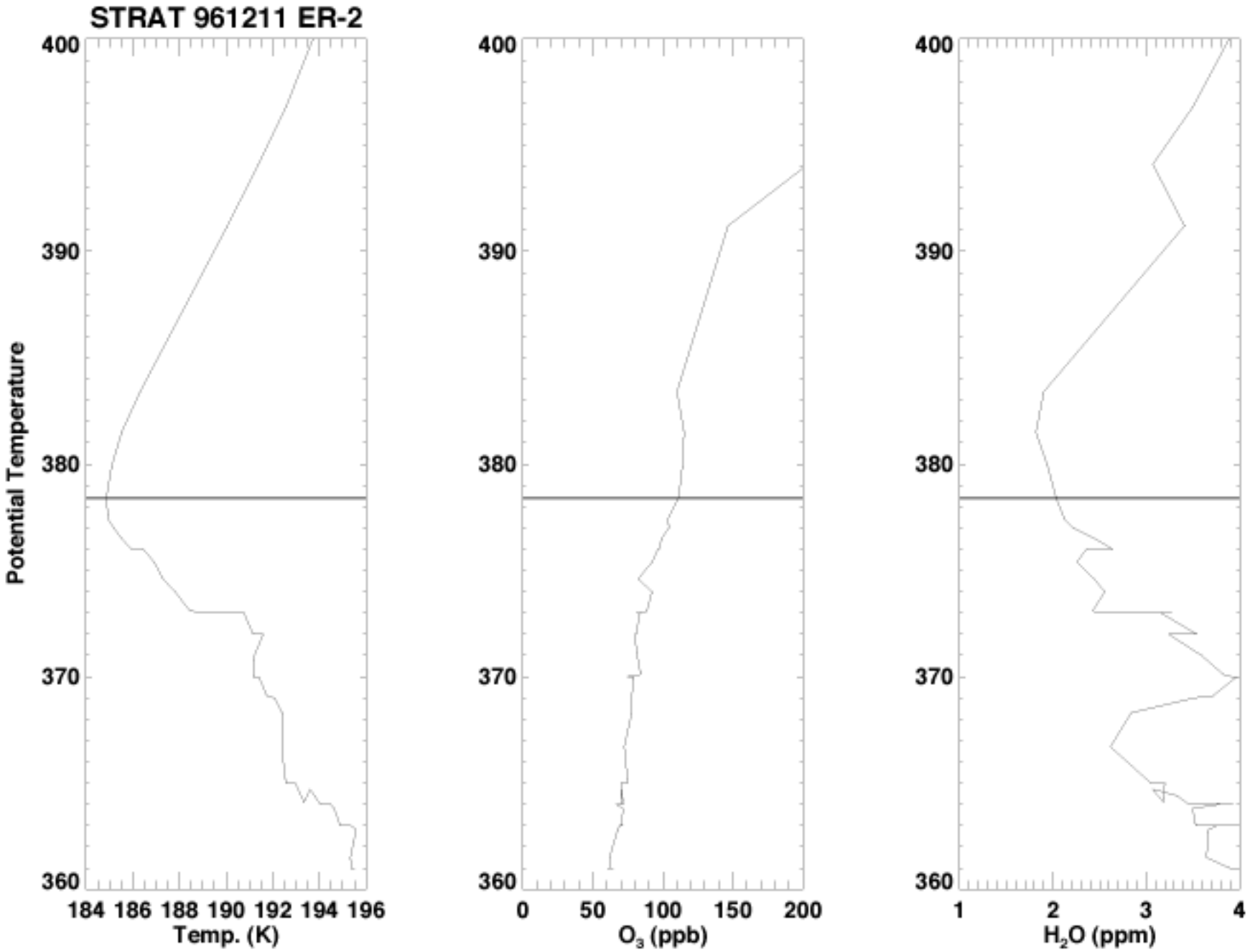
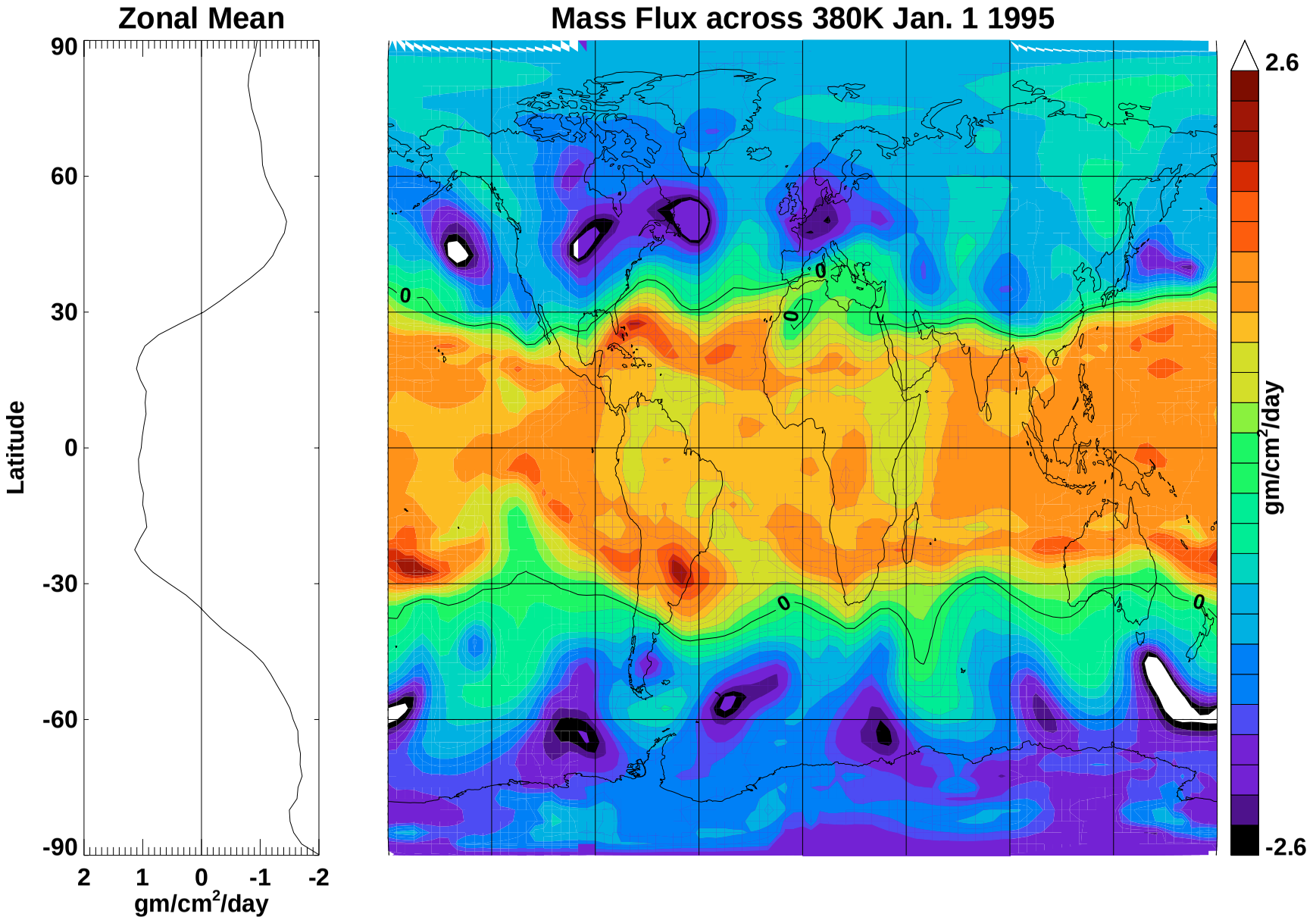

STRAT 961211 ER-2
Potential Temperature
400
390
380
370
360
184 186 188 190 192 194 196
Temp. (K)
0 50 100 150 200
O3 (ppb)
1 2 3 4
H2O (ppm)

Figure 3 (Part a) The mass density of the stratospheric middleworld (mass column between tropopause and 380K surface, see Figure 1) on January 1, 1995 using UKMO data. Note the variable longitudinal structure. (Part b) The mass flux across the 380 K surface, note that the largest downward mass flux occurs where the stratospheric middleworld has the largest mass density (i.e. is more inflated).


Zonal Mean
Mass Flux across 380K Jan. 1 1995
Latitude
90
60
30
0
-30
-60
-90
2
1
0
-1
-2
gm/cm2/day
0
2.6
gm/cm2/day
-2.6

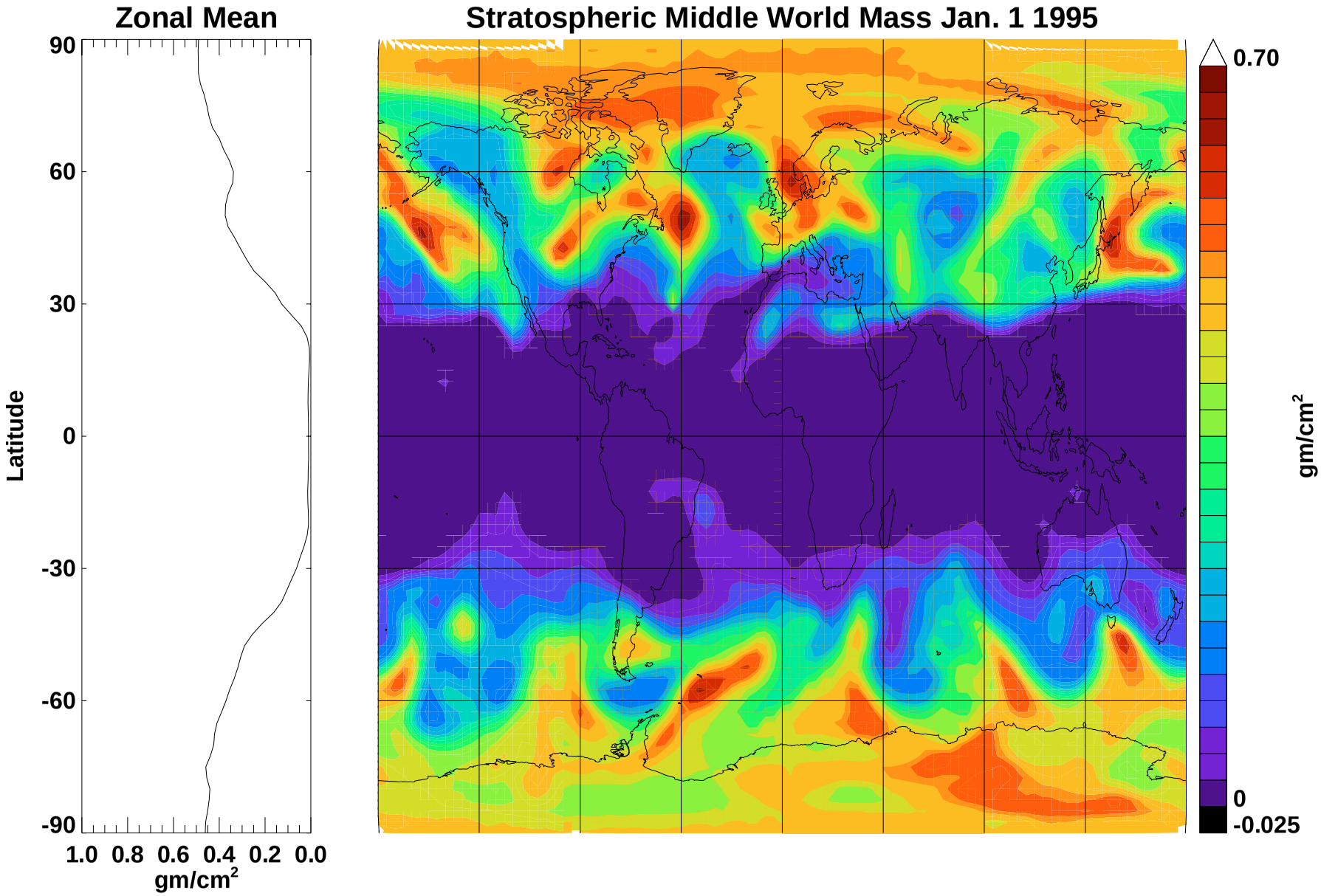
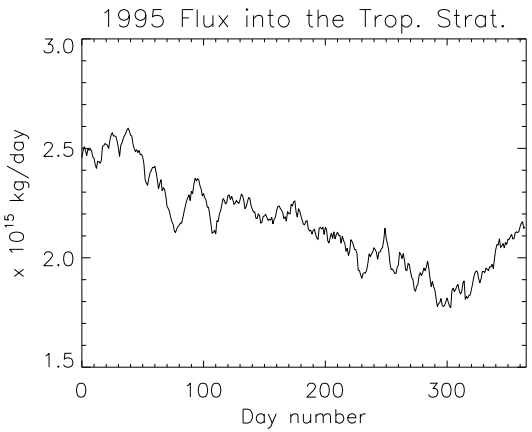
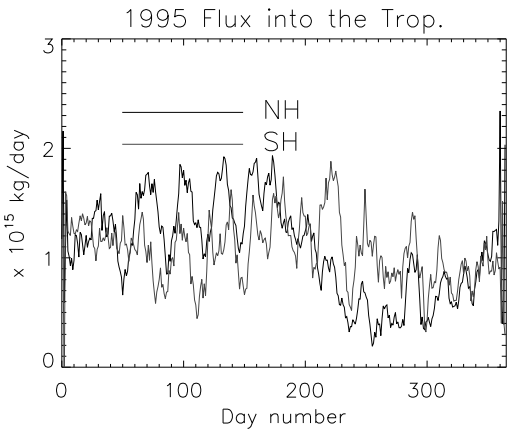
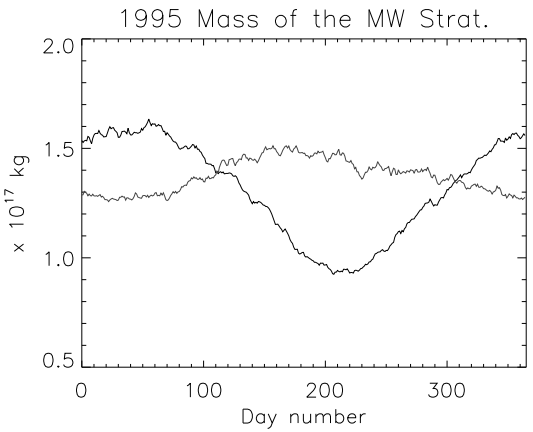
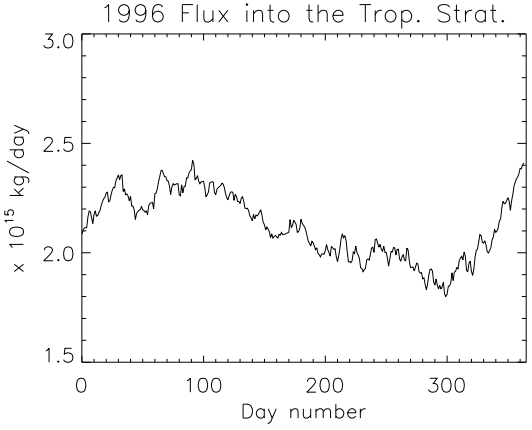

Zonal Mean
Stratospheric Middle World Mass Jan. 1 1995
Latitude
90
60
30
0
-30
-60
-90
1.0 0.8 0.6 0.4 0.2 0.0
gm/cm2
0.70
0
-0.025
gm/cm2

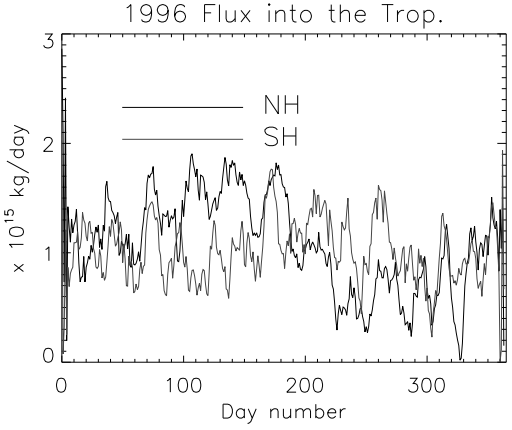
Figure 4. Mass budgets and fluxes for the years 1995-1997 computed from UKMO assimilated data. Left figures show mass flux into the tropical stratosphere across the tropopause. Middle shows the Northern Hemisphere (NH) and Southern Hemisphere (SH) flux from the middleworld into the troposphere. Right shows the total mass of the middleworld. The troposphere mass fluxes have been smoothed with a 5 day box car filter.

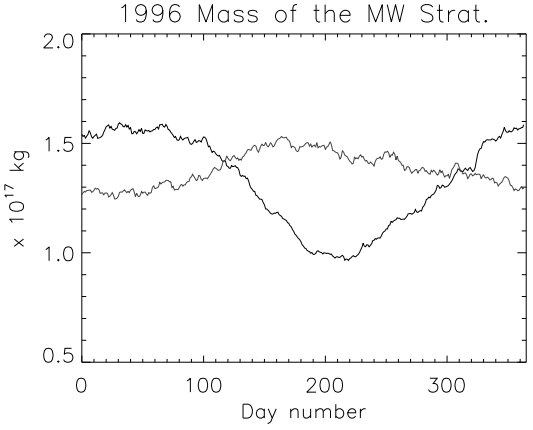

1995 Flux into the Trop. Strat.
x 10^15 kg/day
Day number

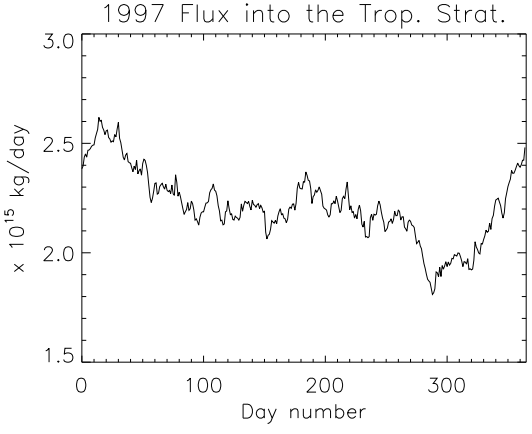

1995 Flux into the Trop.
NH
SH
x 10^15 kg/day
Day number

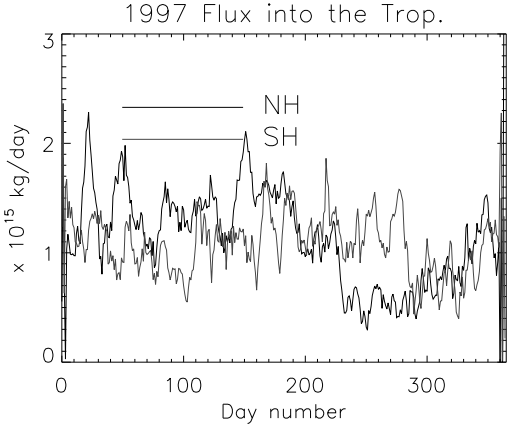

1995 Mass of the MW Strat.
x 10^17 kg
Day number


1996 Flux into the Trop. Strat.
x 10^15 kg/day
Day number


1996 Flux into the Trop.
NH
SH
x 10^15 kg/day
Day number


1996 Mass of the MW Strat.
x 10^17 kg
Day number


1997 Flux into the Trop. Strat.
x 10^15 kg/day
Day number


1997 Flux into the Trop.
NH
SH
x 10^15 kg/day
Day number

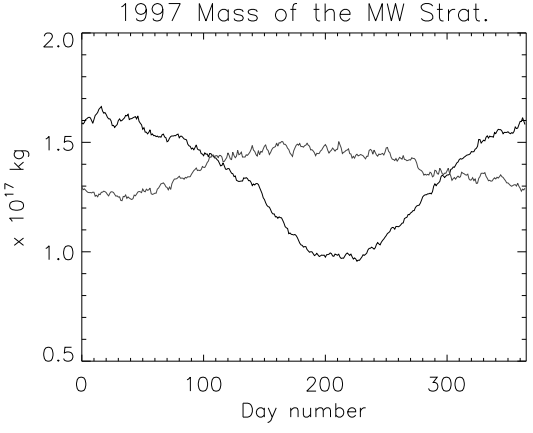

1997 Mass of the MW Strat.
x 10^17 kg
Day number

Figure 5 Comparison of TOMS column ozone with preliminary results from the Combined Model, which has been implemented with parameterized stratospheric chemistry modules. Upper figure, TOMS, lower figure, the Combined model (FVCCM). The model and observations compare well in the tropics and middle latitudes. The chemistry module does not include heterogeneous processes - low Antarctic ozone is being generated dynamically.

Zonally Averaged Total Ozone (DU)

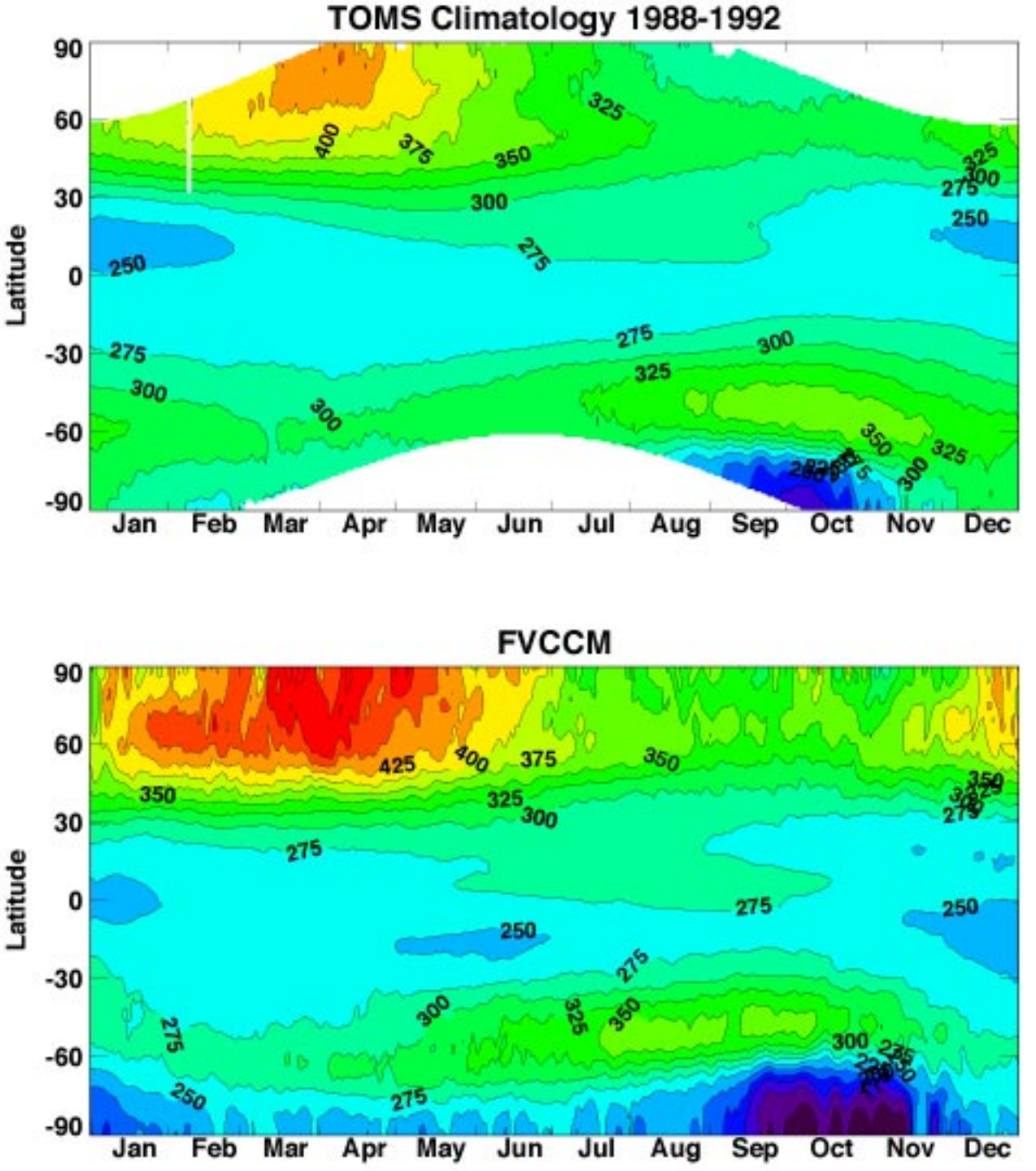


Figure 6. Tropical reservoir dispersal simulation using the trajectory model. An initial distribution of 9,323 parcels are placed in the tropics (< 20^o latitude) as shown (upper left). The simulation is run forward for one year. The other figures show the evolution of the cloud. Parcels below 7 km are not shown. The density is the fraction of parcels in a 5^o by 5 km latitude-height grid. Note the seasonal variability of the distribution. The yellow line is the zonal mean tropopause for the day indicated. White lines are isentropes, 310, 355, 380, 500, 800K.

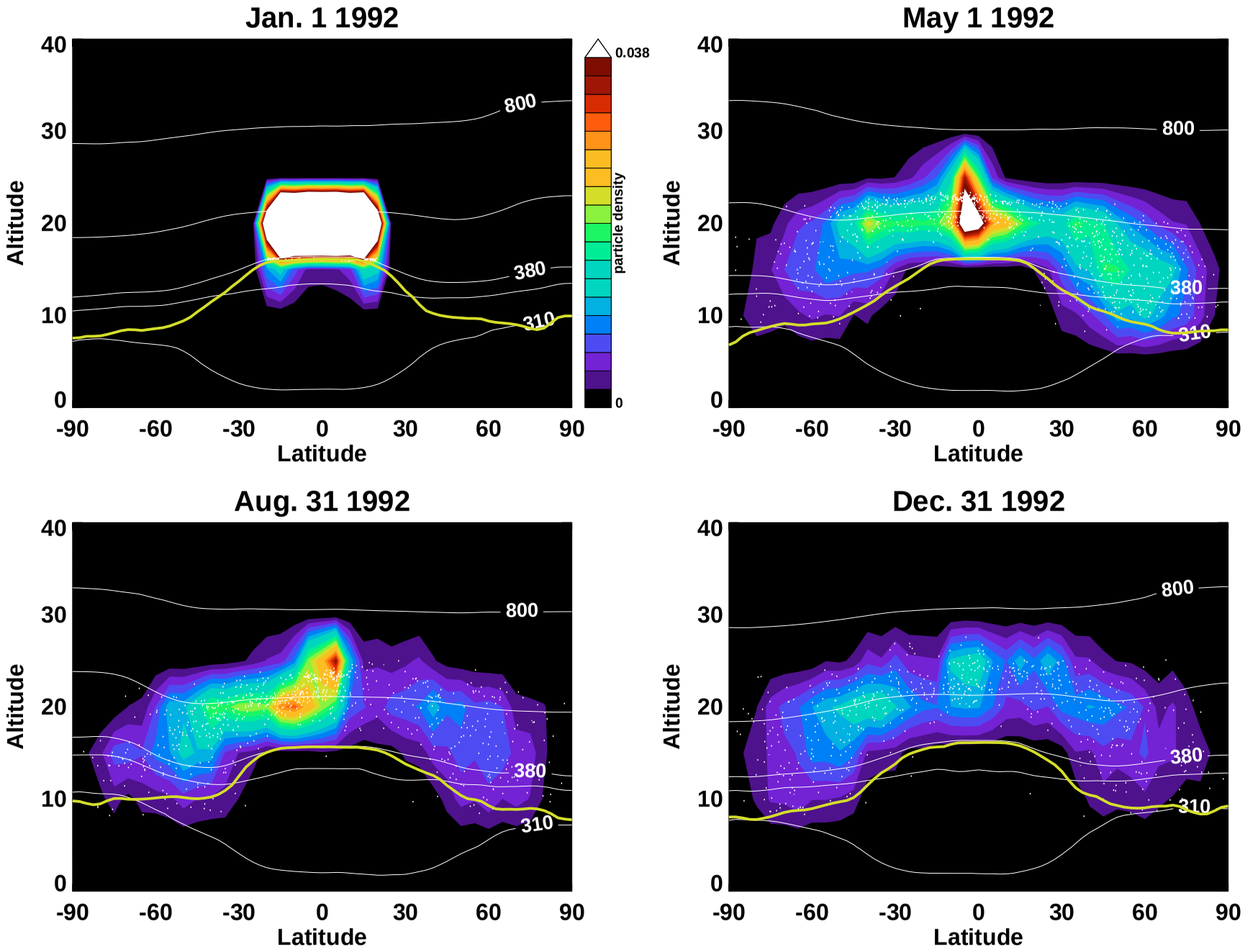
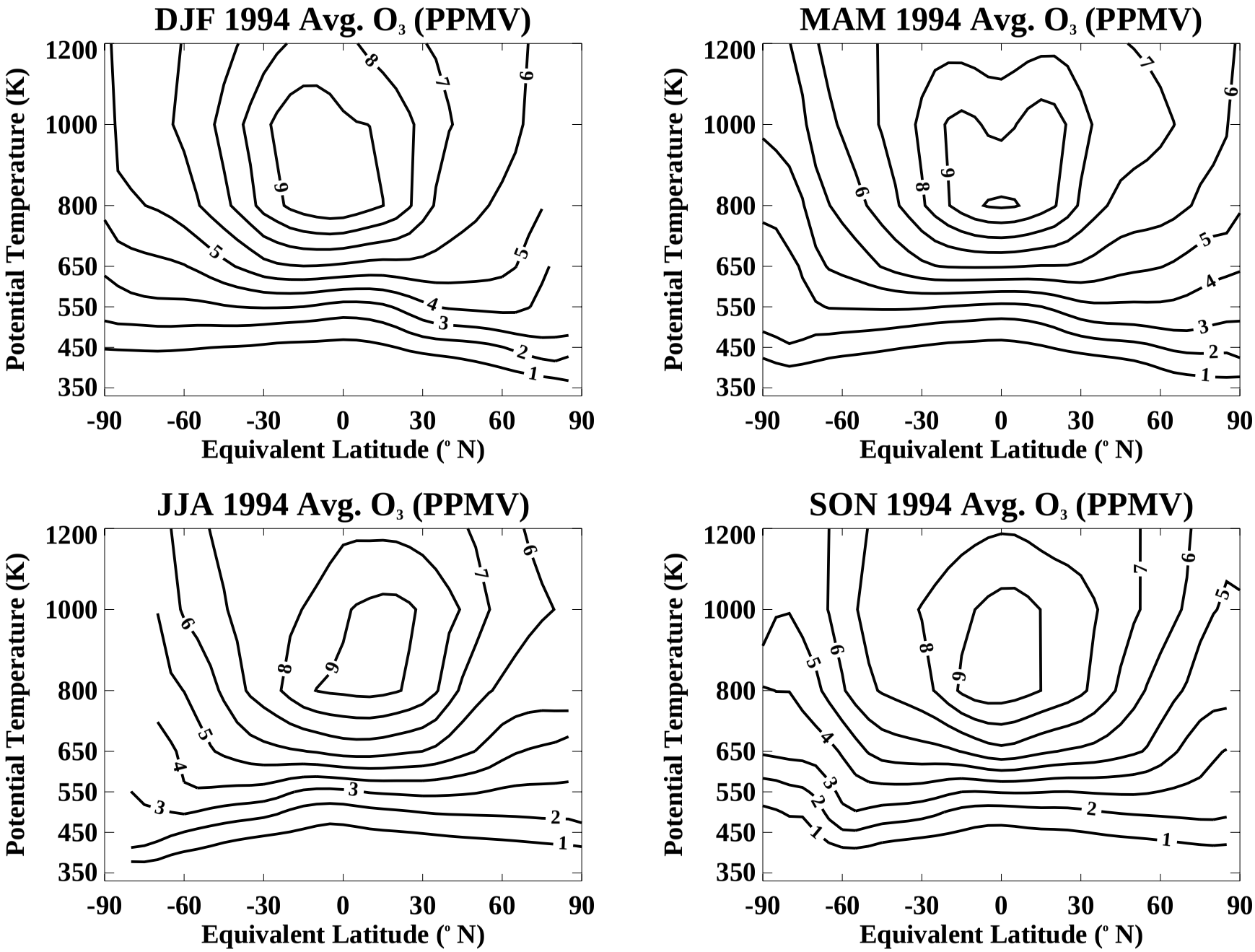
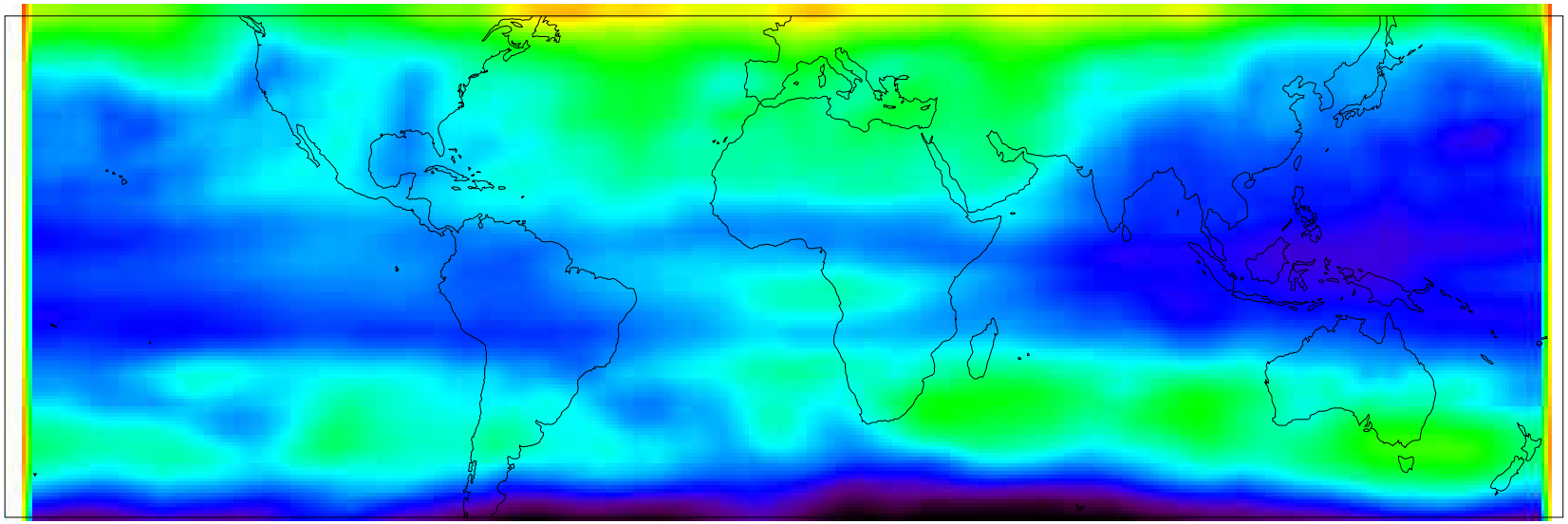

Jan. 1 1992
May 1 1992
Aug. 31 1992
Dec. 31 1992
Altitude
Latitude
particle density
0.038
0
800
380
310
40
30
20
10
0
-90
-60
-30
0
30
60
90

Figure 7 (Part a) Each panel shows our PV/PT ozone climatology from SAGE II (V5.93), UARS/HALOE (V19), and ozonesonde measurements for four 3-month periods in 1993-1994. SAGE II data have been adjusted to agree on average with the HALOE and ozonesonde measurements. PV/PT ozone grids are constructed at ~ 5 day intervals. Each 3-month period is the average of 18 grids (6 grids/month). A map of estimated ozone values can be constructed from these grids given the corresponding potential vorticity and potential temperature data, which are available from a number of meteorological data sources (NCEP reanalysis data were used to construct the current grids). (Part b) Tropospheric ozone computed using the PV/PT technique. Note that the technique allows estimates to be extended into middle latitudes.


DJF 1994 Avg. O3 (PPMV)
MAM 1994 Avg. O3 (PPMV)
JJA 1994 Avg. O3 (PPMV)
SON 1994 Avg. O3 (PPMV)
Potential Temperature (K)
1200
1000
800
650
550
450
350
-90
-60
-30
0
30
60
90
Equivalent Latitude (° N)

Aug 1989 Avg. Tropospheric Residual from PV-Mapping



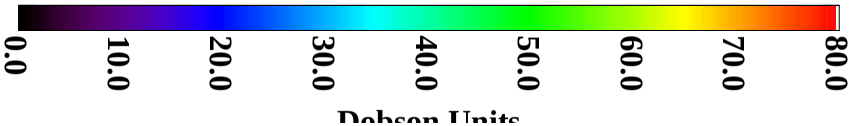
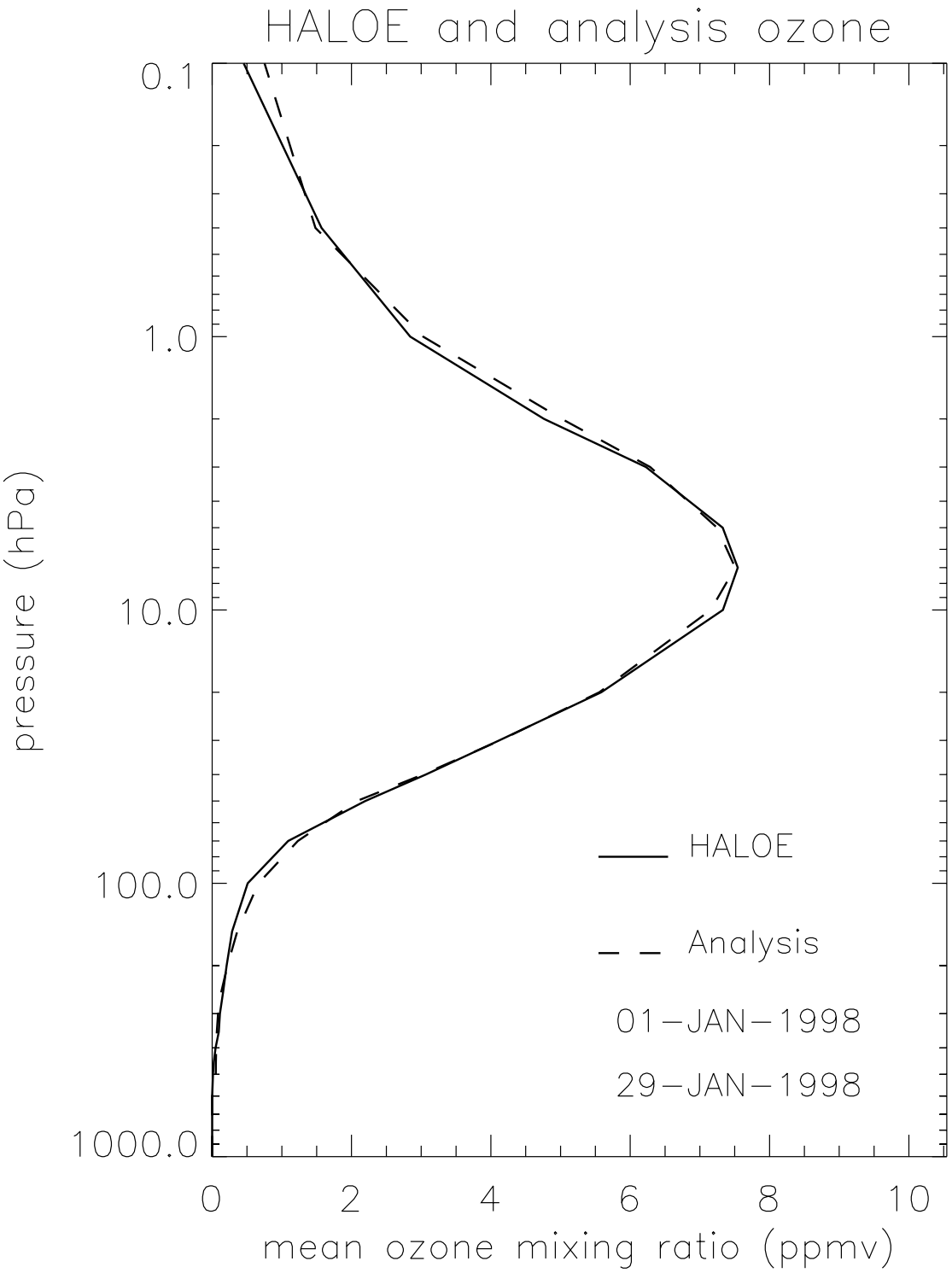
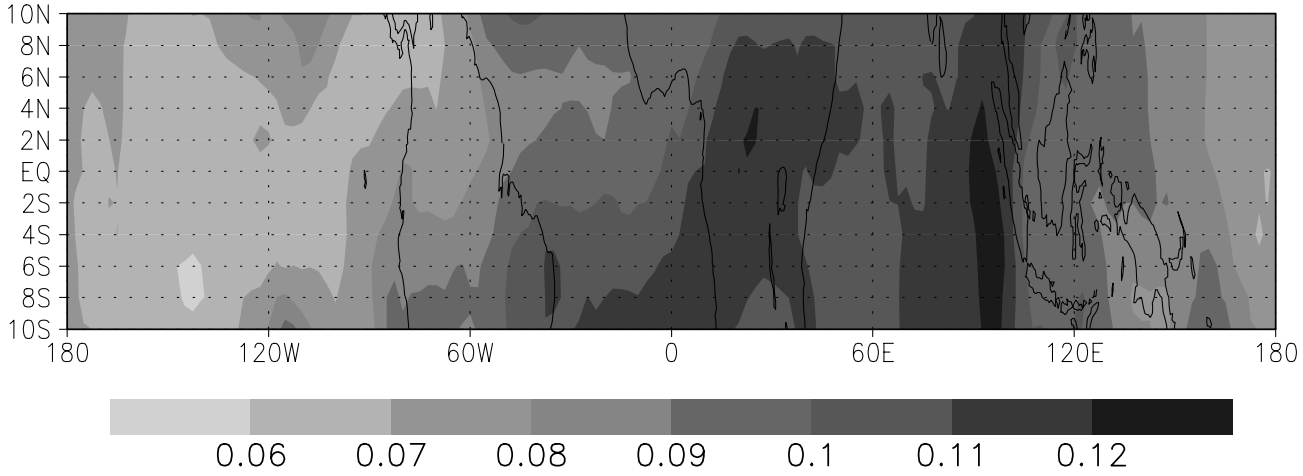


Figure 8. Preliminary results of the assimilation of ozone using TOMS and SBUV. Part a shows the 1998 annual mean comparison with HALOE observations. Part b shows a January 1998 tropical map of stratospheric ozone at two differ


HALOE and analysis ozone
0.1
1.0
10.0
100.0
1000.0
pressure (hPa)
0
2
4
6
8
10
mean ozone mixing ratio (ppmv)
HALOE
Analysis
01–JAN–1998
29–JAN–1998

Mean analyzed (154) ozone mixing ratio [ppmv]
in Jan. 98 at 150 hPa



at 40 hPa

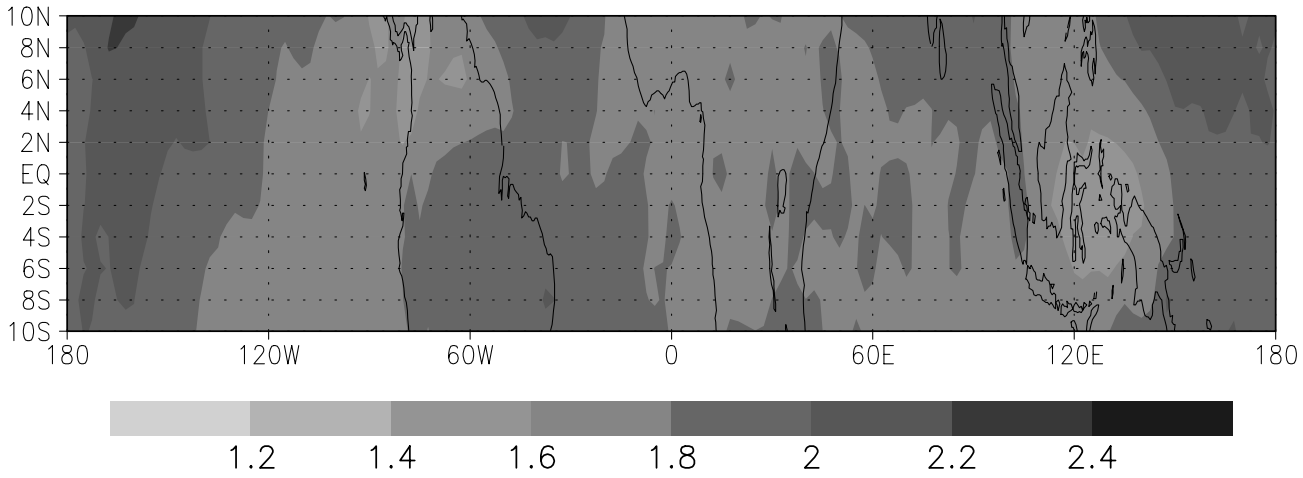


Figure A.1.1-1 Comparison of column ozone from the interactive 2D model for different climate scenarios. The solid line shows the model computed ozone compared with TOMS (dash-triple dot). The other lines show the case for the 2050 scenario. The dashed line is for all greenhouse gases, the dash-dot line is for all greenhouse gases except CO_2. The increase in ozone is due mainly to the reduction in chlorine.

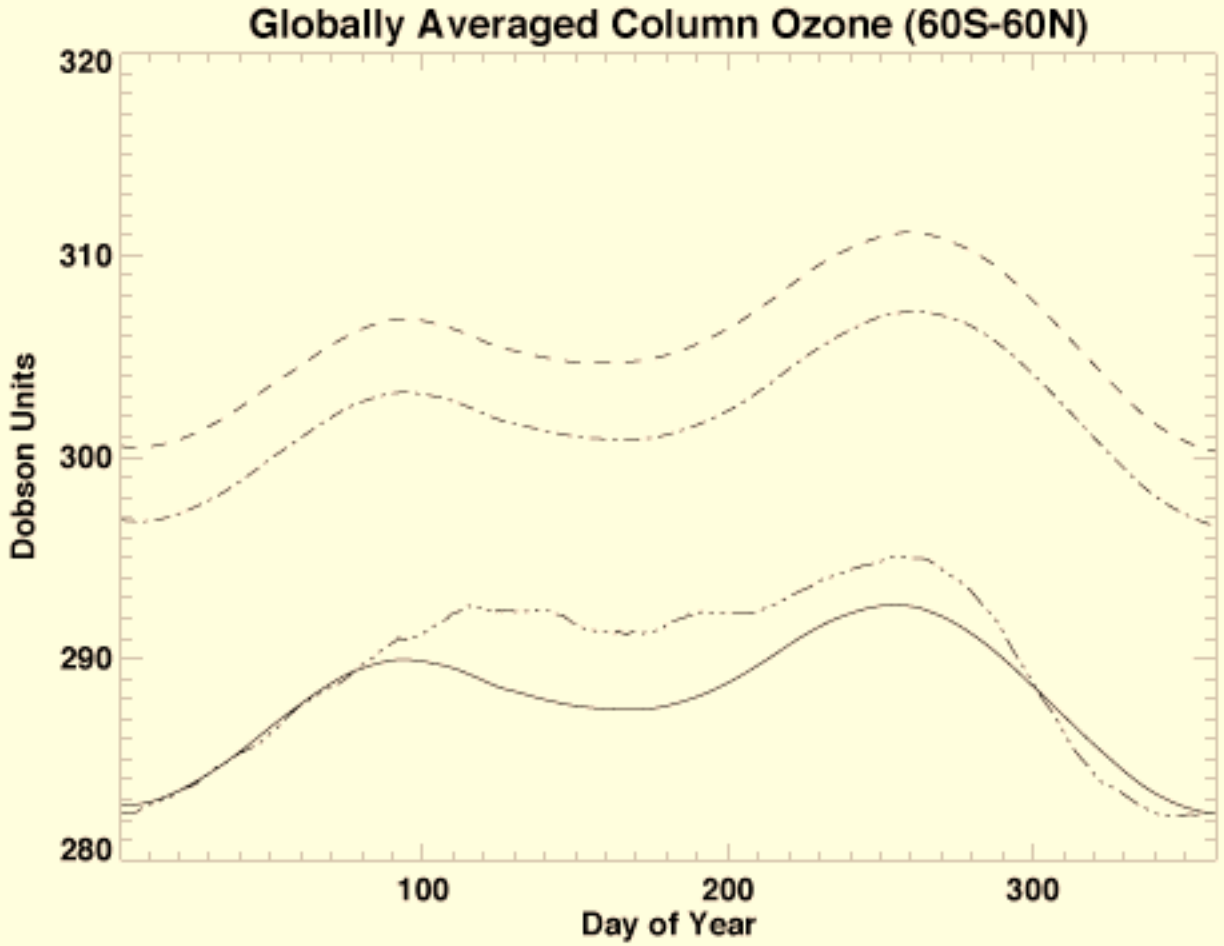
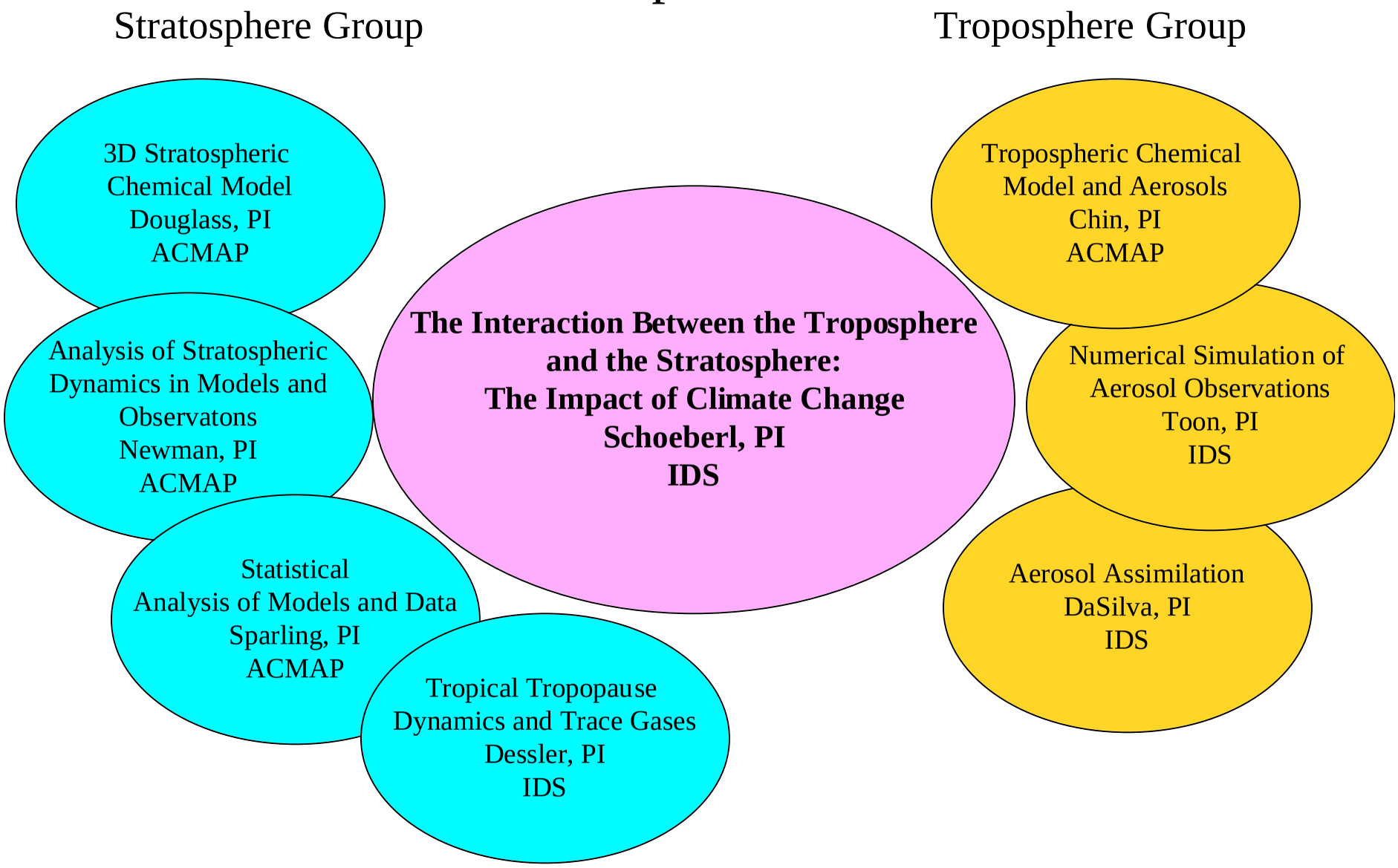

Globally Averaged Column Ozone (60S-60N)
320
310
300
290
280
Dobson Units
100
200
300
Day of Year

Figure B-1 Related IDS and ACMAP proposals.

Figure C.1-1 The latitudinal structure of the long-term, monthly mean temperature in January for ECMWF reanalyses (black curve), the MA/ECHAM4 model (violet), the GEOS-2 model (orange) and the new NASA/NCAR model (red), with the equivalent curves for the remaining 11 GRIPS models in pale blue. Note that the ECMWF reanalyses are in good agreement with radiosonde observations in the tropics.

Inter-relationship between ACMAP and IDS Proposals



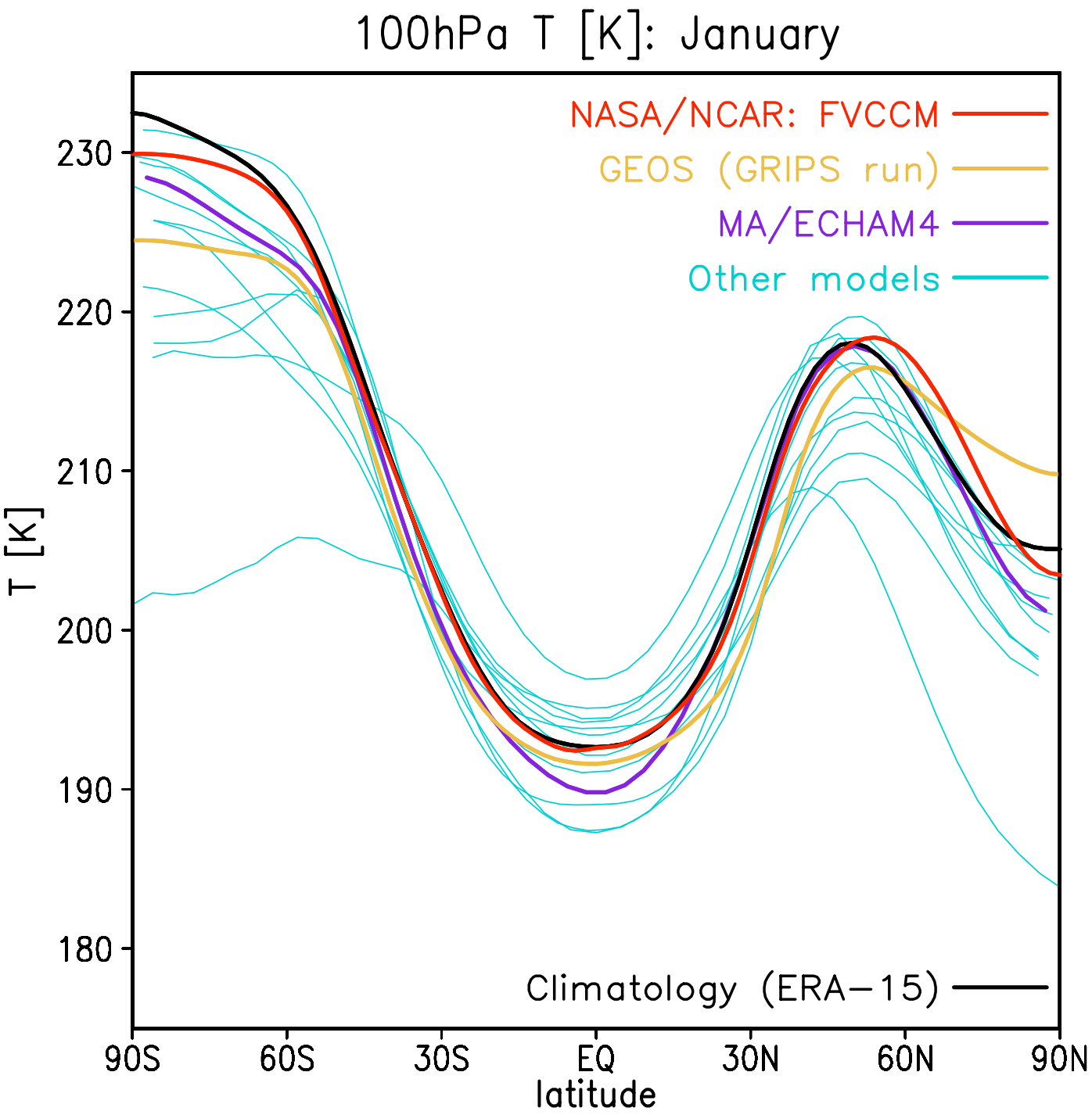

100hPa T [K]: January
NASA/NCAR: FVCCM
GEOS (GRIPS run)
MA/ECHAM4
Other models
Climatology (ERA–15)
T [K]
230
220
210
200
190
180
90S
60S
30S
EQ
30N
60N
90N
latitude

Figure C.1-2
The monthly-mean, zonal-mean methane distribution for January 1980 simulated by the FVCCM with parameterized chemistry. The model was initialized one year prior to this and integrated using observed monthly mean sea surface temperatures and sea ice from the Atmospheric Model Intercomparison Project (AMIP). Four trace gases were included: CH_4, N_2O, odd oxygen and SF_6; these were treated independently using parameterized zonal-mean production and loss rates from the GSFC 2-D model. The simulated trace gas distributions were not coupled to the model's radiation scheme. Compared to observations, the simulated distribution is too peaked in the tropics and the meridional gradient is too uniform; HALOE data show flat isopleths in the tropics and a rapid transition to midlatitude values in the subtropics. This field and the other trace gases suggest that the subtropical barrier in the model is too permeable; the impacts of model resolution will be investigated by increasing the grid from 2 x 2.5 degrees to 1 x 1 degree.

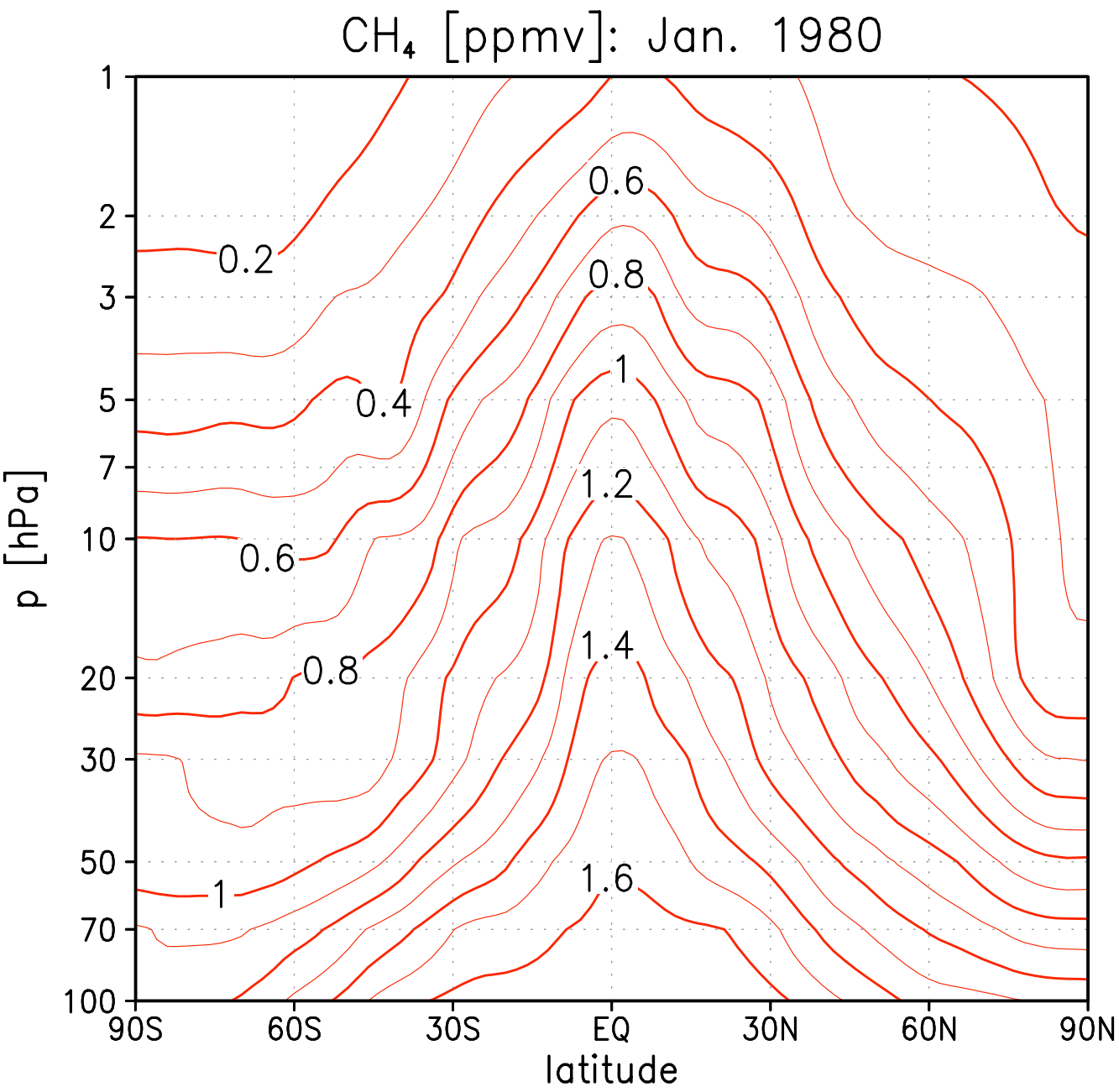

CH4 [ppmv]: Jan. 1980
p [hPa]
1
2
3
5
7
10
20
30
50
70
100
90S
60S
30S
EQ
30N
60N
90N
latitude
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Figure C.1-3
The simulated methane distribution at 10hPa on Dec. 1 1979 from the same model integration as in Figure (Above). This figure illustrates that even though the subtropical barrier is too weak, it does exist. Especially in the northern hemisphere there is a clear distinction between the low mixing ratios in the polar vortex and the high tropical concentrations, with strong gradients in between. A strong wavenumber-1 event is evident in the northern hemisphere, with high tropical values being transported north-eastward over eastern Asia and streaming across the Pacific in the surf zone. In the southern hemisphere the remnants of the polar vortex are seen in distorted filaments of trace gases, which are gradually mixed with surrounding air masses, leading to homogenization of the values in the middle and high latitudes.

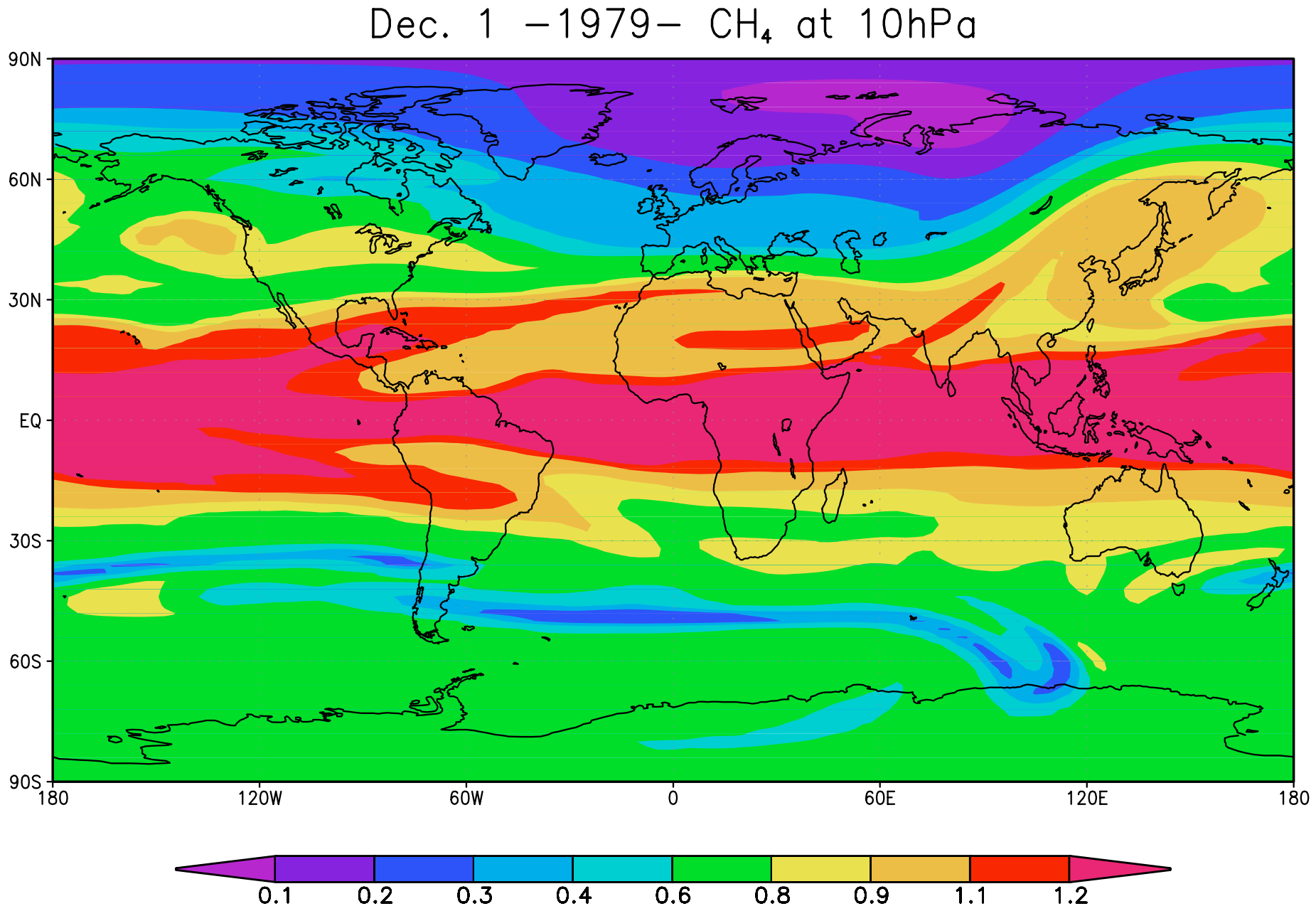
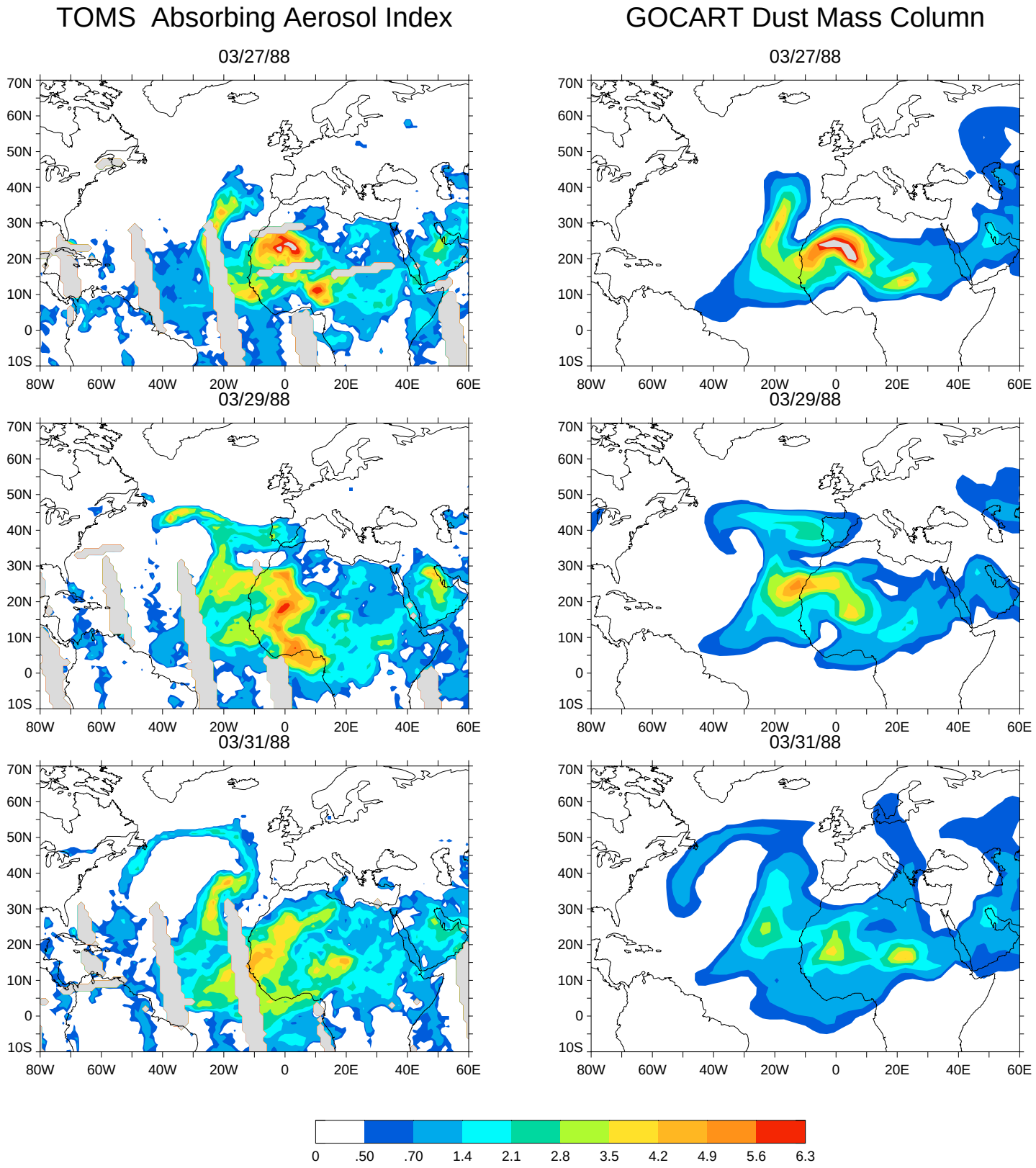
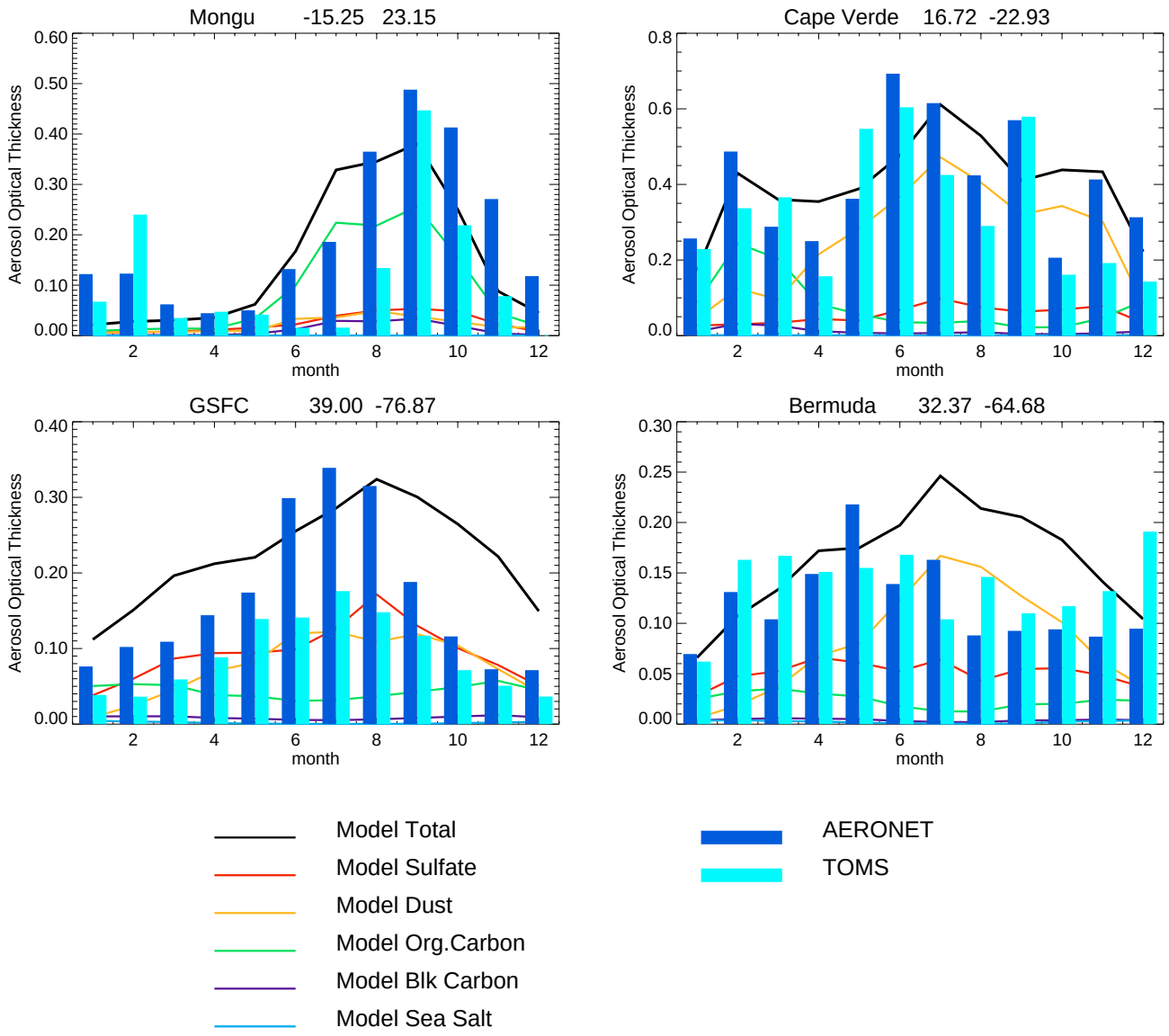

Dec. 1 −1979− CH4 at 10hPa
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
0.1
0.2
0.3
0.4
0.6
0.8
0.9
1.1
1.2

Figure C.5.1-1
Comparison of GOCART model results with TOMS absorbing aerosol index for March 1998. Left panels, TOMS index, right panel, model dust column in $0.4g/M^2$



Comparison of model results with TOMS absorbing aerosol index for March 1988.
Left pannels: TOMS index. Right pannels: model dust column in 0.4g/m2.

Figure C.5.1-2
Comparison of monthly averaged optical thickness from the model with AERONET and TOMS data at 550 nm.



Comparison of monthly avg optical thickness from the model with AERONET and TOMS data at 550 nm.